SCIENCE AND INDUSTRY Sci

VOLUME LV 1947 NUMBER 1

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JANUARY 1947

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THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

January 1947 Vol. LV, No. 1

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The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago 37, Illinois, bimonthly, in January, March, May, July, September, and November. ¶ The subscription price is $6.00 per year, the price of single copies is $1.25. Orders for service of less than a full year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States and its possessions, Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, Guatemala, Haiti, Republic of Honduras, Mexico, Morocco (Spanish Zone), Nicaragua, Panama, Paraguay, Peru, Rio de Oro, El Salvador, Spain (including Balearic Islands, Canary Islands, and the Spanish Offices in Northern Africa; Andorra), Spanish Guinea, Uruguay, and Venezuela. ¶ Postage is charged extra as follows: for Canada and Newfoundland, 24 cents on annual subscriptions (total $6.24); on single copies 4 cents (total $1.29); for all other countries in the Postal Union 60 cents on annual subscriptions (total $6.60), on single copies 10 cents (total $1.35). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in United States currency or its equivalent by postal or express money orders or bank drafts.

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Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit.

Business correspondence should be addressed to The University of Chicago Press, Chicago 37, Ill.

Communications for the editors and manuscripts should be addressed to the Editor of THE JOURNAL OF GEOLOGY, The University of Chicago, Chicago 37, Ill.

Contributors are requested to write scientific and proper names with particular care and in citations to follow the form shown in the pages of the Journal.

Because of the high cost of printing, this Journal has found it necessary to adopt the following rules. ¶ 1. The cost of illustrative material, in excess of $1.50 per page for the article, beyond the cost of type which would have occupied the same space, shall be borne by the author. ¶ 2. The cost of excessive alterations (i.e., changes from the original manuscript) made by the author will be charged to him. ¶ 3. For the present the Journal will supply free 50 reprints (without covers) of each article. Additional reprints must be ordered in advance of publication; rates will be furnished on request.

The articles in this Journal are indexed in the *International Index to Periodicals*, New York, N.Y.

Applications for permission to quote from this Journal should be addressed to The University of Chicago Press, and will be freely granted.

Entered as second-class matter February 29, 1944, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.
Acceptance for mailing at special rate of postage provided for in United States Postal Act of October 3, 1917, Section 1103, amended February 28, 1925, authorized July 15, 1918.

[PRINTED IN U.S.A.]

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A SEMI-QUARTERLY

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VOLUME LV

JANUARY–NOVEMBER, 1947

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS

THE CAMBRIDGE UNIVERSITY PRESS, LONDON

PUBLISHED JANUARY, MARCH, MAY, JULY, SEPTEMBER,
AND NOVEMBER, 1947

COMPOSED AND PRINTED BY THE UNIVERSITY OF CHICAGO
PRESS, CHICAGO, ILLINOIS, U.S.A.

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VOLUME LV NUMBER 1

THE JOURNAL OF GEOLOGY

January 1947

REFRACTION OF OCEAN WAVES: A PROCESS LINKING UNDERWATER TOPOGRAPHY TO BEACH EROSION

WALTER H. MUNK AND MELVIN A. TRAYLOR
Scripps Institution of Oceanography[1]

ABSTRACT

Waves out at sea, though usually forming a complex pattern, have essentially the same characteristics over large distances. Upon entering shallow water, these waves are transformed under the influence of bottom features, and such transformations may be so marked that breaker heights may vary greatly over short distances along the shore. The effect of bottom features upon waves can largely be interpreted in terms of a simple physical process—wave refraction. In turn, wave refraction may be responsible for alteration of the bottom features by accumulation or removal of sediments and, in this manner, be an important factor in beach erosion.

In this report the role of wave refraction is first reviewed in the light of other processes affecting the transformation of waves in shallow water. The mechanism of refraction is illustrated by means of a few idealized examples, such as the refraction pattern along a straight uniformly sloping beach, over a submarine canyon and ridge, and around a headland. Next it is shown that extreme variations in breaker height along the beach north of La Jolla, California, can be computed for typical swell conditions, taking the complex local bottom topography and the orientation of the coastline into consideration. These changes are computed from refraction diagrams for typical swell conditions, and they compare favorably with observed changes in wave height, thus indicating that wave refraction is the primary mechanism controlling changes in wave height along a beach, and that friction, diffraction, and other processes can be of secondary importance only. Finally, it is noted that the transportation of sediments is dependent upon longshore currents, rip currents, and horizontal diffusion and that all these factors are greatly influenced by the existing refraction pattern.

INTRODUCTION

Waves may have traveled many days and for thousands of miles before they approach shore and become transformed under the influence of the ocean bottom. By that time the long, low, regular undulations, called "swell," may be all but hidden beneath a local chop. As soon as the swell enters shallow water, it "feels" bottom, and a striking rejuvenation takes place. This change occurs in water of depth less than one-half the wave length, where wave length is defined as the horizontal distance between adjacent crests. The wave velocity and length decrease while the height usually increases, so that the wave gradually steepens. As the waves approach the surf zone, this process of steepening accelerates suddenly—the crests rise sharply from the water surface, become peaked, and break.

The changes just described are most noticeable for a swell from a distant storm. Waves formed by a near-by storm, or by winds blowing directly toward the coast, have already considerable steepness out at sea; the transforma-

[1] Contribution from the Scripps Institution of Oceanography, New Series, No. 307. This work represents results of research carried out for the Hydrographic Office, the Office of Naval Research, and the Bureau of Ships of the Navy Department under contract with the University of California.

tion in shallow water, though similar, is therefore much less pronounced.

Only the period, defined as the time interval between the appearance of two successive crests at a fixed point, remains constant as waves travel into shallow water. According to theory, well substantiated by observation, wave velocity and length depend almost entirely upon wave period and depth (see the Appendix). For a regular wave system the velocity and length will therefore be constant along any given depth contour.

The discussion so far has dealt with changes in the character of the waves which are the direct result of changes in velocity and length. Except under very special conditions, the wave height will, however, not be uniform along any given depth contour, because the effect of refraction over an irregular bottom enters. This effect causes waves to bend, and the bending of the wave crests in turn affects the wave height. With irregular bottom topography, waves are bent differently at different sections of a beach, and the wave height will vary along the beach. The present study is concerned principally with a discussion of the refraction effects.

The refraction of ocean waves and other problems dealing with the transformation of waves in shallow water have been studied intensively during the war in connection with the development of a method for forecasting surf conditions for amphibious operations.[2] Practically all changes in the character of the waves in shallow water can be accounted for theoretically by assuming conservation of energy and irrotational wave motion, and it has been shown that the conclusions based on theory are in good agreement with observations.[3]

WAVE REFRACTION

THE PHYSICAL NATURE OF WAVE REFRACTION

Wave crests approaching a coastline at an angle tend to swing parallel to shore (Fig. 1). This happens because the wave velocity decreases as the depth decreases, so that the portion of the crest nearer the shore moves slowly while the portion of the crest in deeper water races ahead. To illustrate this, consider two surfboarders on the same crest, traveling along the lines A and B (Fig. 1). Surfboarder B always travels faster than A, and the two tend to become more nearly aligned with the shoreline as they travel into shallow water.

The process is similar to the one causing the bending of light rays in optical systems and has therefore been termed "refraction." In the case of straight parallel contours, the analogy can be carried further, because the changes in direction of light waves and ocean waves are governed by Snell's law:[4]

$$\frac{\sin \alpha}{\sin \alpha_0} = \frac{C}{C_0}, \qquad (1)$$

where α is the angle between the wave crest and the contours at any depth, C the wave velocity at the same depth, and the parameters with subscript o refer only to deep water where the direction and velocity are constant.

REFRACTION DIAGRAMS

In the case of a more complicated bottom topography for which the depth contours are not straight and parallel,

[2] "Breakers and Surf, Principles in Forecasting," *Hydrographic Office, U.S. Navy, No. 234* (November, 1944).

[3] H. U. Sverdrup and W. H. Munk, "Theoretical and Empirical Relations in Forecasting Breakers and Surf," *Trans. Amer. Geoph. Union*, Vol. XXVII, No. 6 (December, 1946), pp. 828–36.

[4] Pp. 6–7 of ftn. 2.

changes in wave direction and height can be found graphically by constructing a "refraction diagram," a term first used by O'Brien and Mason.[5]

A refraction diagram is one on which the position of wave crests at the sea surface is shown by a series of lines. These are evenly spaced in deep water—that is, in water of depth greater than half the wave length. Beyond this depth the effect of bottom contours on any of the wave characteristics is negligible. At shallower depths the relation between wave velocity and water depth is known (see Appendix), and a refraction diagram can be constructed by advancing various points on a crest through distances determined from any chosen time interval and the average depth. The direction of advance is drawn normal to the crest. In Figure 1, for example, the chosen time interval is one wave period, and the distance A_0—A'. The distance B_0—B' represents the advance of point B during the same time interval, but for the average depth between B_0 and B'. The lines A_0—A' and B_0—B' are normal to the wave crests. By locating a set of points, A', B', C', ... , the new crest can be found with sufficient accuracy by drawing a smooth line through these points. Advancing one wave length at a time, the crests may be carried into any depth of water desired, and the completed diagram shows the continuous change in the direction of a wave advancing from deep into shallow water.

Description of a practical procedure for constructing refraction diagrams, together with the necessary graphs and tables, can be found in the forecasting manual.[6] The completed diagram can be interpreted in one of two ways: (1) As a series of lines representing the positions of a *single* wave crest at various times as the crest advances toward shore. Crest interval is then defined as the interval between these times. In Figure 1 the crest interval equals one wave period. (2) As a series of lines representing the position of certain wave crests at a *single instant;* a crest interval of *one* wave length means that every crest is represented (Fig. 1), because the advance of any point on a crest during one wave period equals one wave length by definition. A crest interval of *two* wave lengths means that only every second wave crest is shown; a crest interval of *one-half* wave length, that the position of every crest and trough is shown.

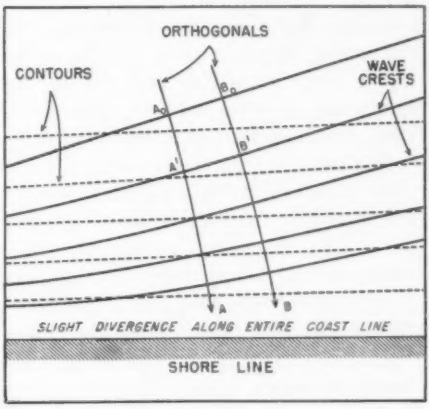


FIG. 1.—Refraction of waves along beach with straight parallel depth contours. The wave crest along the orthogonal B is always in deeper water than along A and therefore moves with greater velocity. As a result, the waves tend to turn parallel to shore.

EFFECT OF REFRACTION ON WAVE HEIGHT

Wave height is defined as the vertical distance between crest and trough. In order to evaluate the effect of refraction on wave height, a set of orthogonals, that

[5] "A Summary of the Theory of Oscillatory Waves," *Technical Report No. 2, Beach Erosion Board* (1940).

[6] Pp. 31–34 of ftn. 2.

is, a family of lines which are everywhere perpendicular to the wave crests, must be constructed. The lines A_o–A and B_o–B in Figure 1 are orthogonals; they may be visualized as the wakes behind two surfboards which are continuously oriented normal to the crest, that is, in the direction of wave motion. Assuming that the wave *energy* is transmitted in the direction of wave motion, the total flow of energy between two orthogonals must remain constant. Thus if orthogonals *converge*, the crests are *compressed*, and the energy per unit crest length is relatively *large;* if orthogonals *diverge*, the crests are *stretched*, and the energy per unit crest length is relatively *small*.

For practical purposes one must deal with wave heights rather than with wave energies, but these are related. In deep water the height of oscillatory waves varies as the *square root* of energy, and this relation holds with good approximation in shallow water until the waves "peak" just prior to breaking. The breaking waves, with their sharp crests isolated by long flat troughs, have the appearance of so-called "solitary" waves, for which the height is proportional to the *cube root* of the energy. Let H designate the wave height and s the distance between adjacent orthogonals on the refraction diagram. Parameters with subscript o again apply in deep water, those with subscripts b at the breaker point, and parameters without subscript at any depth intermediary between deep water and the breaking-point. Then

$$\frac{H}{H_0} = \gamma K\,, \qquad \frac{H_b}{H_0} = \gamma_b K_b\,, \quad (2a,\ b)$$

where γ and γ_b have constant values along a fixed depth contour, and where

$$K = \sqrt[2]{s_0/s}\,, \qquad K_b = \sqrt[3]{s_0/s_b}\,, \quad (3a,\ b)$$

may vary along a depth contour and will be referred to as the "refraction factors." The complete derivation of these equations is given in the Appendix.

Any *variation* in wave height along a fixed depth contour depends only upon the refraction factor. The variation can be computed from the change in distance between orthogonals according to equations (3), depending upon whether one deals with conditions in shallow water or along the breaker line. Again it should be stressed that the absolute wave height depends also upon several other factors which are implicitly contained in the parameters γ and γ_b of equations (2) (see Appendix).

Equations (2) are derived from the postulates that the energy flows along orthogonals and that energy is conserved. This in turn implies two assumptions: (1) the effect of *diffraction* (which would bring about flow of energy across orthogonals from region of high waves to regions of low waves) can be neglected and (2) the effect of bottom friction is negligible. The validity of these assumptions is borne out by the good agreement between computed changes in breaker height according to equations (2), and observations along the beach north of La Jolla, California (Fig. 16). There has been a tendency in the literature to emphasize the effect of bottom friction on wave motion and other wave characteristics. Not only the evidence presented in this paper, but also studies dealing with the generation of waves by wind,[7] and with absolute changes of wave height in shallow water and the dynamics of breaking waves,[8] indicate that wave motion in general is not appreciably affected by frictional processes.

[7] H. U. Sverdrup and W. H. Munk, "Empirical and Theoretical Relations between Wind, Sea and Swell," *Trans. Amer. Geoph. Union*, Vol. XXVII, No. 6 (December, 1946), pp. 823–27.

[8] Pp. 830–32 of ftn. 3.

REFRACTION TYPE EXAMPLES

Beach with straight and parallel depth contours.—For this simple case the change in wave direction can be expressed analytically by equation (1). Figure 1 is a schematic drawing of wave refraction along a straight coastline with parallel depth contours. Plate I, *A*, is an aerial photograph showing long waves from the south-southwest coming into the beach north of Oceanside, California. There is a divergence of the orthogonals indicated by the values of s computed from the equation[9]

$$\frac{s}{s_0} = \frac{\cos \alpha}{\cos \alpha_0}. \qquad (4)$$

[9] Pp. 20–21 of ftn. 2.

Combining equations (1), (3), and (4) leads to

$$\left.\begin{aligned} K &= \left[\frac{\cos^2 \alpha_0}{1-\left(\frac{C}{C_0}\sin \alpha_0\right)^2}\right]^{1/4}, \\ K_b &= \left[\frac{\cos^2 \alpha_0}{1-\left(\frac{C_b}{C_0}\sin \alpha_0\right)^2}\right]^{1/8}, \end{aligned}\right\} \qquad (5a, b)$$

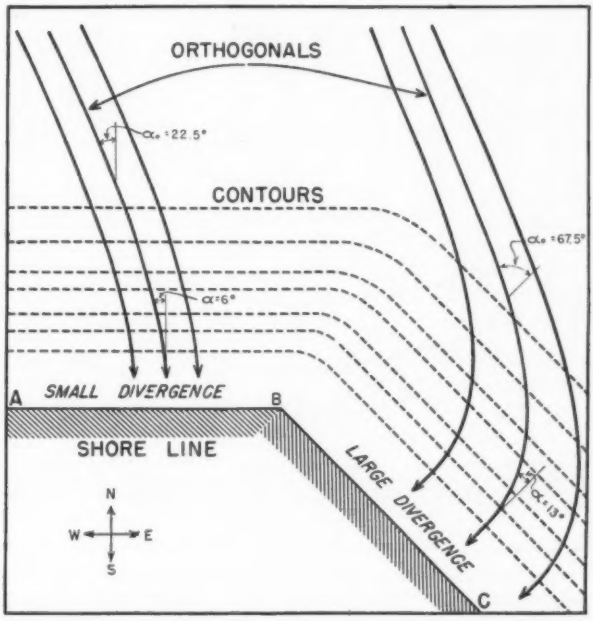


FIG. 2.—Refraction of waves along two sections of straight beaches with different exposures. The divergence along section *A–B* is less than along *B–C*, and the wave height along *A–B* exceeds therefore the wave height along *B–C*.

where C/C_0 is found from equation (A7) in the Appendix.

Waves coming from an angle into a beach with straight and parallel depth contours are reduced in height according to equations (5), but the reduction is uniform along the entire beach, and no *variation* in wave height *along* the beach will result. As an example of variation in wave height, consider a coastline which

forms a sharp bend at point *B* (Fig. 2). On both sides of point *B* the coastline and the depth contours are straight and parallel. Assume that waves of 14-second period come from the north-northwest. The angle α is drawn between the orthogonals and the bottom gradient, which is consistent with our earlier definition. Table 1 gives the computed direction and relative height at the 10-foot contour, which is assumed to lie outside the breaker zone. Along the beach section *A–B*, which is relatively exposed to the incoming swell, waves are about 50 per cent higher than along section *B–C*. This can also be seen from the fact that the divergence of orthogonals along *A–B* is less than the divergence along *B–C* (Fig. 2).

Submarine canyons.—Portions of wave crests over the center of a canyon are in deeper water and move ahead faster than the portions on either side (Fig. 3). Consequently, the waves fan out, resulting in divergence (low waves) over the head of the canyon and convergence (high waves) on either side. Fishermen take advantage of this feature when they anchor near the head of a submarine canyon. Plate II is an aerial photograph of waves over the submarine canyon at Redondo, California. The approximate position of the canyon is indicated. The wave crests bend sharply over the canyon walls. Variations in wave height can be recognized by the prominence of the wave crests on either side of the canyon

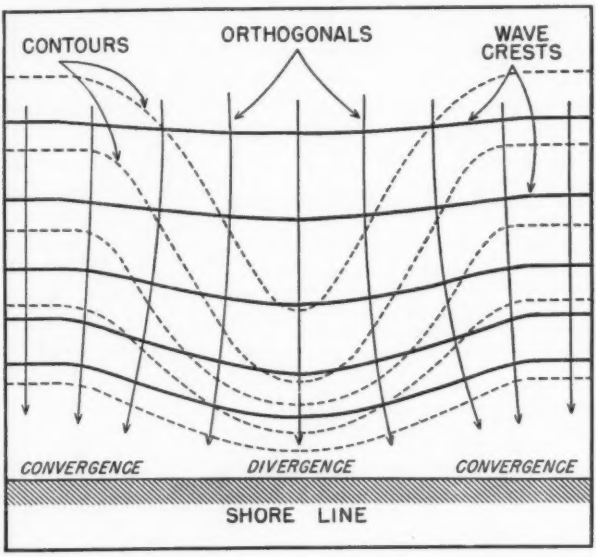


FIG. 3.—Refraction of waves by a submarine canyon. Waves move faster over the canyon than on either side of the canyon, resulting in divergence (low waves) over the mouth of the canyon and convergence (high waves) on either side.

TABLE 1

Section of Coast Line (Fig. 2)	A–B	B–C
Wave angle in deep water (α_0)	22.5°	67.5°
Wave angle at 10-foot depth (eq. [1])*	6.0°	13.0°
Refraction factor (eq. [5*a*])	0.97	0.63

* The value of C/C_0 is obtained from "Breakers and Surf," *op. cit.*, Pl. I, and equals 0.25.

compared to the crests directly over the canyon and by the variation in the width of the surf zone.

Submarine ridges.—Underwater ridges near shore have an effect opposite to that of canyons. Waves passing over the ridge are in shallower water and are therefore retarded, and on either side waves move ahead, creating a convergence over the ridge (Fig. 4). This is borne out by frequent observations of unusually violent breakers over the shoal portion of underwater ridges. An aerial photograph take over the northern shore of Oahu, T.H. (Pl. I, *B*), illustrates the lagging of the wave crests over a submarine ridge and the resulting convergence. Figure 5 illustrates the same features over a sand bank opposite the mouth of Mission Bay, San Diego, California. In the case of Mission Bay the refraction pattern is somewhat affected by the tidal flow through the outlet.

Abrupt changes in depth along coral islands lead to particularly well-defined refraction patterns. Plate III shows two channels in the coral reef around Guam; the waves are seen to bend sharply ahead over the channels, where they are lower than on either side of the channels. The photograph also shows the formation of multiple crests just inside the reef, a phenomenon often observed in regions of abrupt depth changes, and one which has never been properly explained.

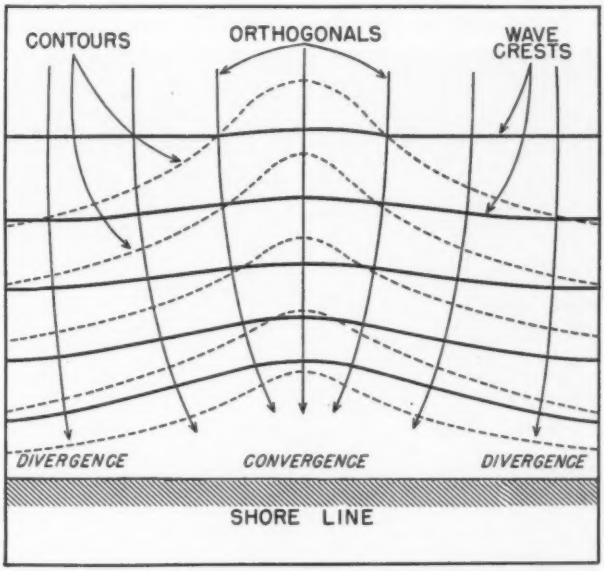


FIG. 4.—Refraction of waves by a submarine ridge. Directly over the ridge waves lag behind, and on either side waves move ahead, creating a convergence (high waves) over the ridge.

Headlands.—Since waves are retarded by shallow water, they will bend around headlands, points, and jetties. Plate IV, *A*, shows an irregular train of waves turning around Point Loma into San Diego Bay.

Under special conditions, such as portrayed in the aerial photograph of the hook of Cape Cod, Massachusetts (Pl. IV, *B*), waves may bend 180°, or even more, before they break. Such extreme

refraction is associated with a very large divergence, which explains the shelter usually provided by protruding land masses.

Bays and islands.—Waves will be retarded along the sides of a bay but move relatively rapidly elsewhere. As a result, the crests will bend *into* the bay (Pl. V). The divergence will be largest at the sides of the bay, least opposite the mouth, especially if waves head directly into the bay. In the case of small islands in the path of an advancing swell the resulting refraction pattern is more complicated (Fig. 6). Offshore in the lee of the island, wave trains which have bent around both sides of the island meet and pass through each other, and a confused cross-sea results.[10] Where the bottom shoals gradually near shore, then drops off steeply, waves may be bent so effectively around an island that the lee shore offers no protection whatsoever.[11] Some coral islands have these characteristics.

WAVE REFRACTION ALONG THE BEACH NORTH OF LA JOLLA, CALIFORNIA

ORIGIN OF WAVES REACHING LA JOLLA

In order to apply the principles of refraction to an actual situation, it is first necessary to determine the periods and directions of waves that will be encountered. For that purpose the character of the waves at La Jolla resulting from typical meteorological situations will be tabulated below. The paths and

FIG. 5.—Refraction of waves over sand bar outside of Mission Bay, San Diego, California (cf. Fig. 4) The outflowing tide may have further strengthened certain features in the existing refraction pattern. (Official photograph, United States Navy.)

[10] Pp. 12–18 of ftn. 2.

[11] Robert S. Arthur, "Refraction of Water Waves by Islands and Shoals with Circular Bottom-Contours," *Trans. Amer. Geoph. Union*, Vol. XXVII (April, 1946), pp. 168–77.

nature of the generating areas are shown schematically in Figure 7; the corresponding character of the waves at La Jolla, in Figure 7, *B*.

Situation A (*winter*).—Waves generated by cyclones originating at the east coast of Asia and moving along the usual cyclone path into the Gulf of Alaska:

Waves generated in the southern segments of these cyclones reach La Jolla in 2–5 days as a long-period (11–15 seconds) swell, with heights varying between 3–7 feet, according to the intensity of the cyclone. The wave energy reaching La Jolla is reduced by the offlying islands, especially San Clemente and Santa Catalina (Fig. 7, *A*). The cyclones often stagnate in the Gulf of Alaska, and the coasts of British Columbia, Washington, Oregon, and northern California will be hit by a heavy swell, whereas southern California will be protected by Point Conception, which cuts off La Jolla from waves from directions much north of WNW.

Situation B (*winter*).—Waves generated behind cold fronts that come into the coastal regions:

These waves have short periods (7–10 seconds), large heights (4–12 feet), and usually come from a W to NW direction.

Situation C (*summer*).—Waves generated by winds in the northeast periphery of the Pacific High:

Usually the period of the waves will vary from 6 to 9 seconds, the height from 2 to 5 feet. The common direction is from WNW to NW.

Situation D (*summer*).—Waves generated in the Southern Hemisphere:

FIG. 6.—Refraction of waves behind a small island. The portion of the wave passing just to the right of the island is refracted to the left; the portion passing just to the left of the island is refracted to the right. The resulting crisscross pattern gives rise to a confused sea in the lee of the island, and the island may offer little or no shelter.

The so-called "southern swell" comes from S to SSW, is of very long period (13–20 seconds), and is usually 3–5 feet high. This is the only direction from which waves can reach La Jolla without being broken up by offlying islands.[12] There is strong evidence that this swell has been generated by the winter storms of the Southern Hemisphere, but, owing to an almost complete lack of weather observations, this has not been verified.

Situation E (*spring*).—Wind waves generated in local low-pressure regions:

Local low-pressure regions, which are usually not forecast, give rise to W or NW winds with

[12] Plate I, *A*, is an aerial photograph of a southern swell coming into Oceanside, Calif.

velocities up to 30 knots. These winds raise waves of 5–7 second-periods, 10–15 feet-heights. Such situations are likely to occur a number of times each spring, occasionally during winter and summer, but rarely during fall.

The character of the waves caused by these five meteorologic situations is summarized in Figure 7, *B*. Each rectangle shows typical height-period combinations corresponding to situations *A*–*E*.

LOCAL TOPOGRAPHY

The coast between Point La Jolla and the Scripps Institution pier is ideally suited for a study of changes in wave height. It is known locally that waves are usually low near the Beach Club, then increase sharply about 3,000 feet north of the Beach Club, and fall off a little in the vicinity of the Scripps Institution pier (Pl. VI). Breaker heights at different sections of this 1-mile stretch of beach generally differ by a factor of 3.

Such unusually large variations in breaker height can be associated with the complex submarine topography and coastline in this region. Two submarine canyons, La Jolla Canyon and its steep-walled tributary, Scripps Canyon, reach within 1,000 feet of shore (Pl. VI). These canyons have been sounded more extensively than any other submarine canyons in the world.

The walls of La Jolla Canyon are relatively gentle except locally where slopes of 100 per cent are found. Scripps Canyon on the other hand has extremely steep walls. Numerous places have been located where the slopes are so steep that the sounding lead slides down the slope after hitting bottom. The steepest measured slope has a drop of 230 feet in a horizontal distance of 30 feet. The canyon has an inner gorge which is so narrow in places that it was difficult to locate. . . . .[13]

The coast line, which is oriented NNE–SSW between Scripps pier and the Beach Club, makes an almost right-angle turn 1,000 feet south of the Beach Club and projects about 3,000 feet in a WNW direction. Point La Jolla is located at the end of this break in the coast line (Pl. VI). Beyond Point La Jolla the coast continues its NNE–SSW trend. In the vicinity of the Beach Club some protection from the usual WNW and W swell is afforded by Point La Jolla, and even more by the shoal area off this point.

TABLE 2

	Figure No.				
	8	9	10	11	12
Wave direction	WNW	WNW	W	WNW	SSW
Wave period	14	12	12	8	16
Crest interval/period	1	1	1	2	1
Meteorological situation	A	A	A	B, C, or E	D

REFRACTION DIAGRAMS

The refraction diagrams (Figs. 8–12) were drawn as described in the manual on breaker and surf forecasting. Table 2 gives the assumed wave direction (direction from which the wave comes in deep water), wave period, crest interval, and the corresponding meteorological situation for each of the five figures.

[13] F. P. Shepard and K. O. Emery, "Submarine Topography off the California Coast," *Geol. Soc. Amer., Special Papers, No. 31* (May 28, 1941).

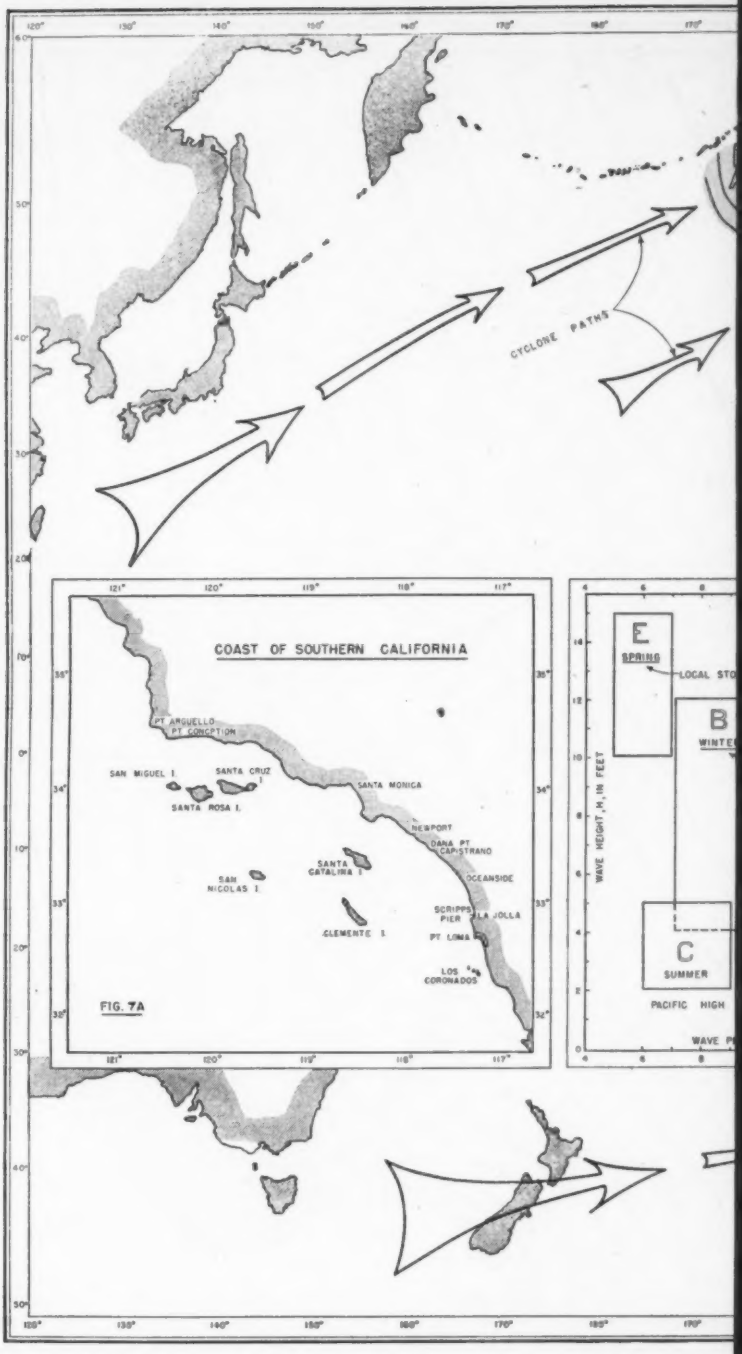
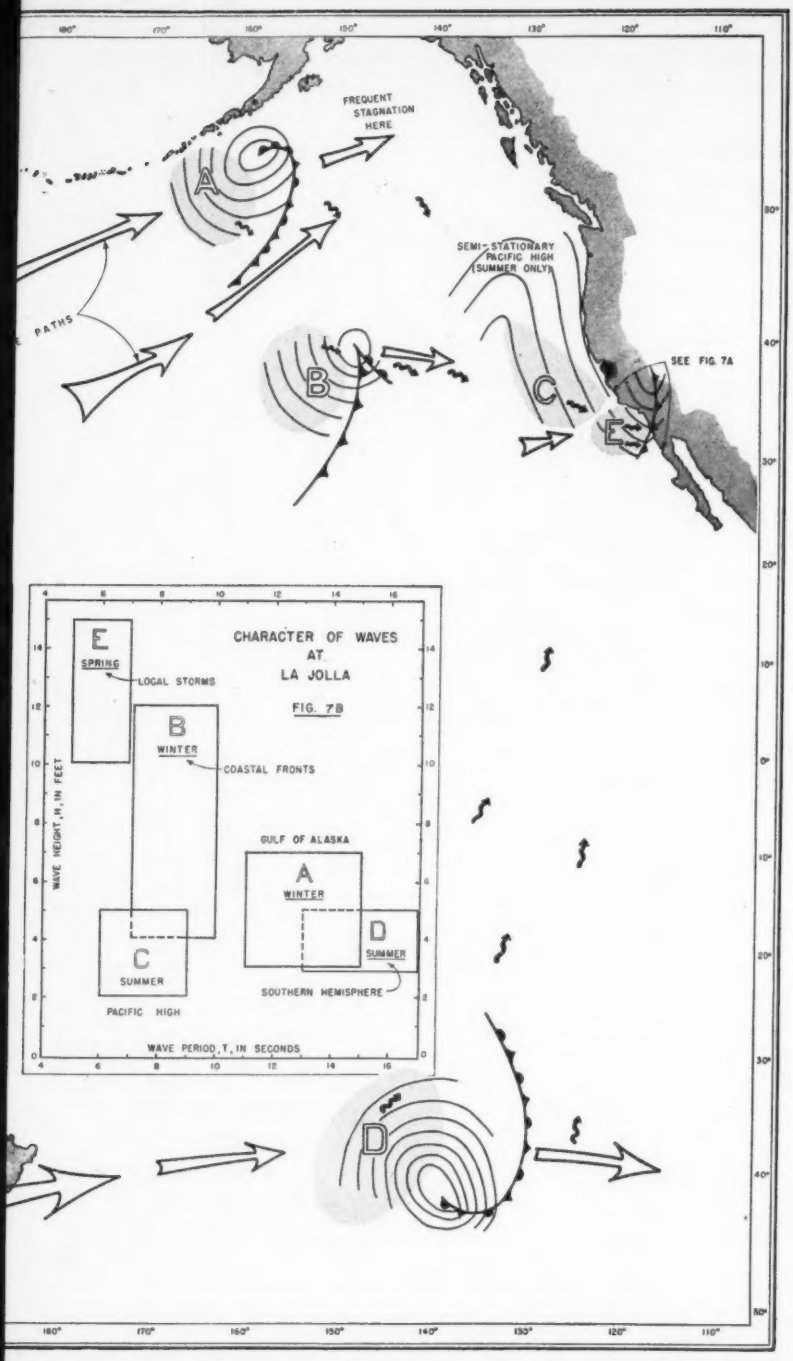


FIG. 7.—Origin of waves reaching La Jolla, California. The capital letters on the l
La Jolla to waves of heights and periods shown in Figure 7, *B*. Figure 7, *A* is a chart of th
large chart represent typical fetches, that is, areas where the waves are generated. The isoba
The large open arrows represent typical paths of the storm systems. The wavy arrows indica
represent the nature of the meteorological situations with any degree of accuracy but is su
systems over widely separated areas of the Pacific Ocean.



pital letters on the large chart represent typical meteorological situations, which give rise at
7, *A* is a chart of the region near La Jolla on an enlarged scale. The shaded areas on the
generated. The isobaric pattern and the nature of the meteorological fronts are also indicated.
he wavy arrows indicate the direction of the waves leaving the storm systems. The figure cannot
e of accuracy but is supposed to emphasize that waves reaching La Jolla are the result of storm

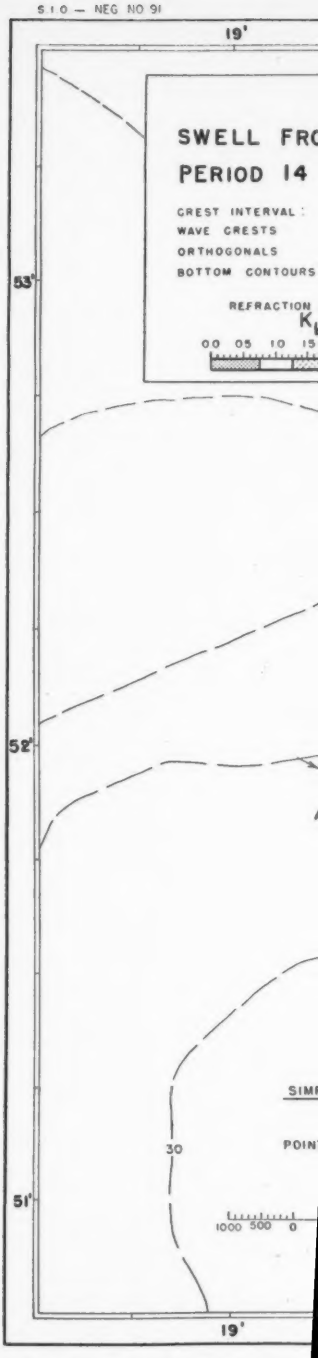
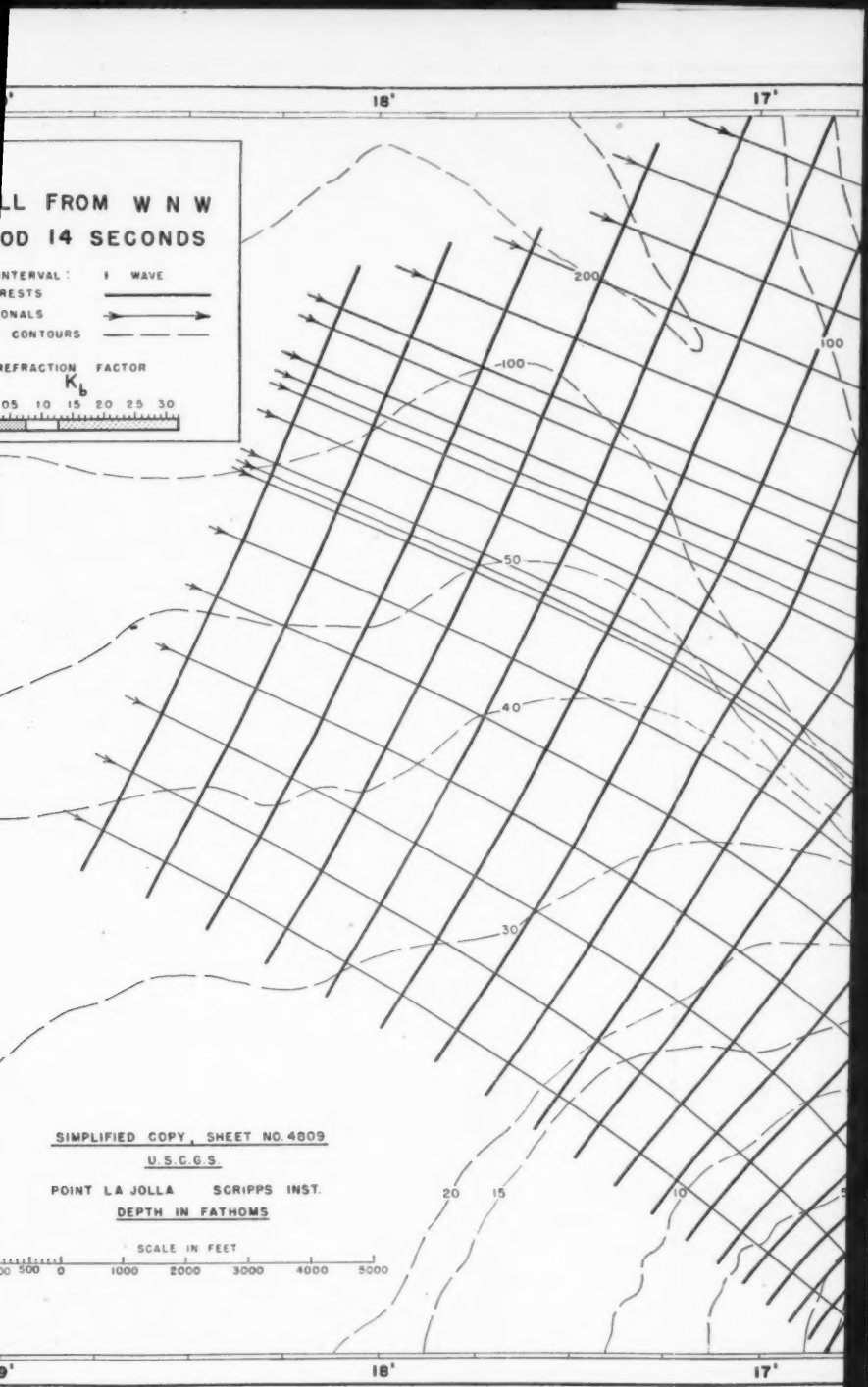
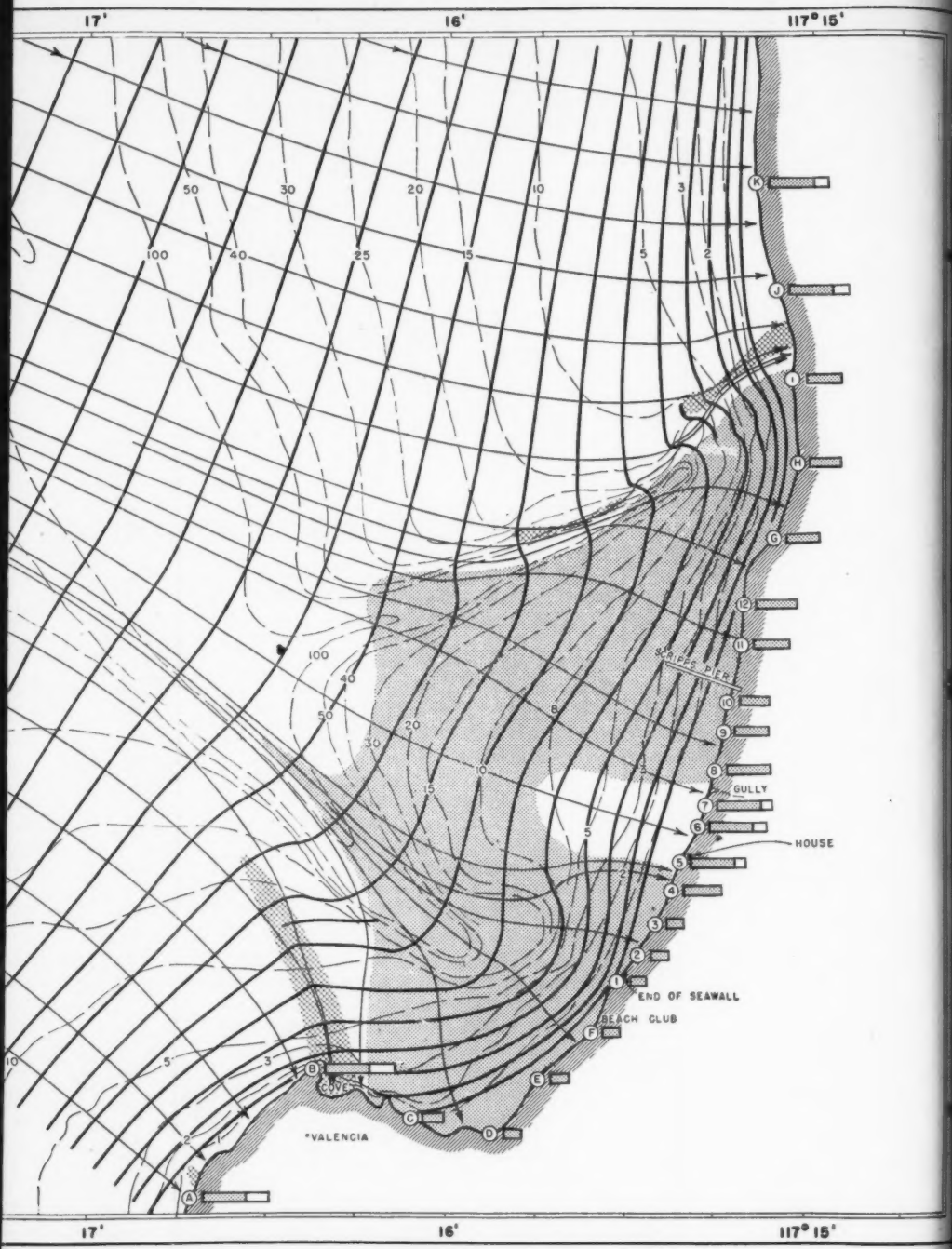


FIG. 8.—Refraction diagram for 14
indicate zones of convergence ($K > 1.$
beach. The general refraction pattern



ram for 14-second waves from the west-northwest. Heavy solid lines show positions of wave crests, the s
e ($K > 1.25$); the dotted regions indicate zones of divergence ($K < 0.75$). The lengths of the rectangles
n pattern conforms with the schematic drawing of Fig. 3.



s of wave crests, the solid lines with arrowheads give orthogonals, and dashed lines are depth contours. The crosshatched re
gths of the rectangles opposite the shore stations are proportional to K_b and thus indicate the variation of breaker heights alon

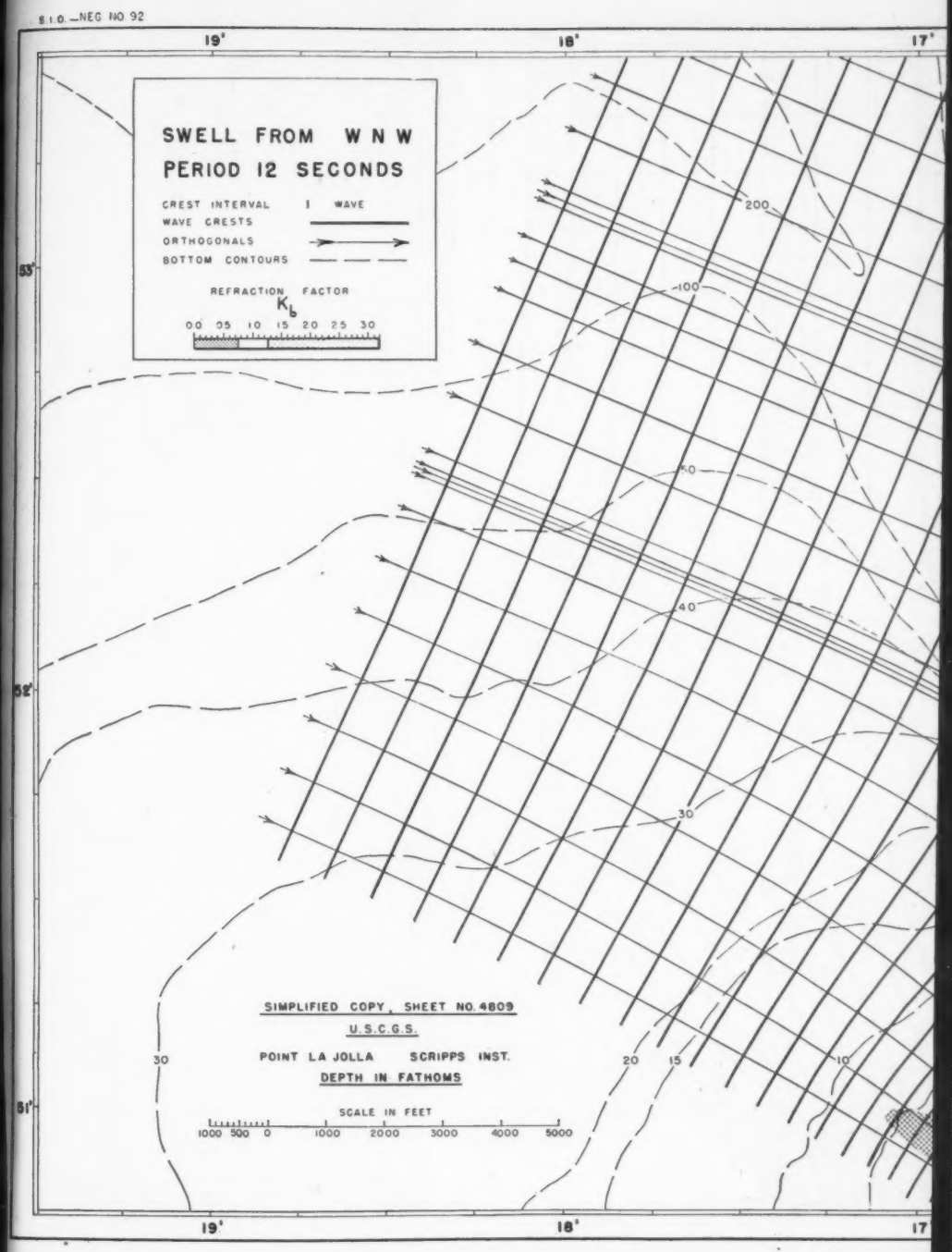
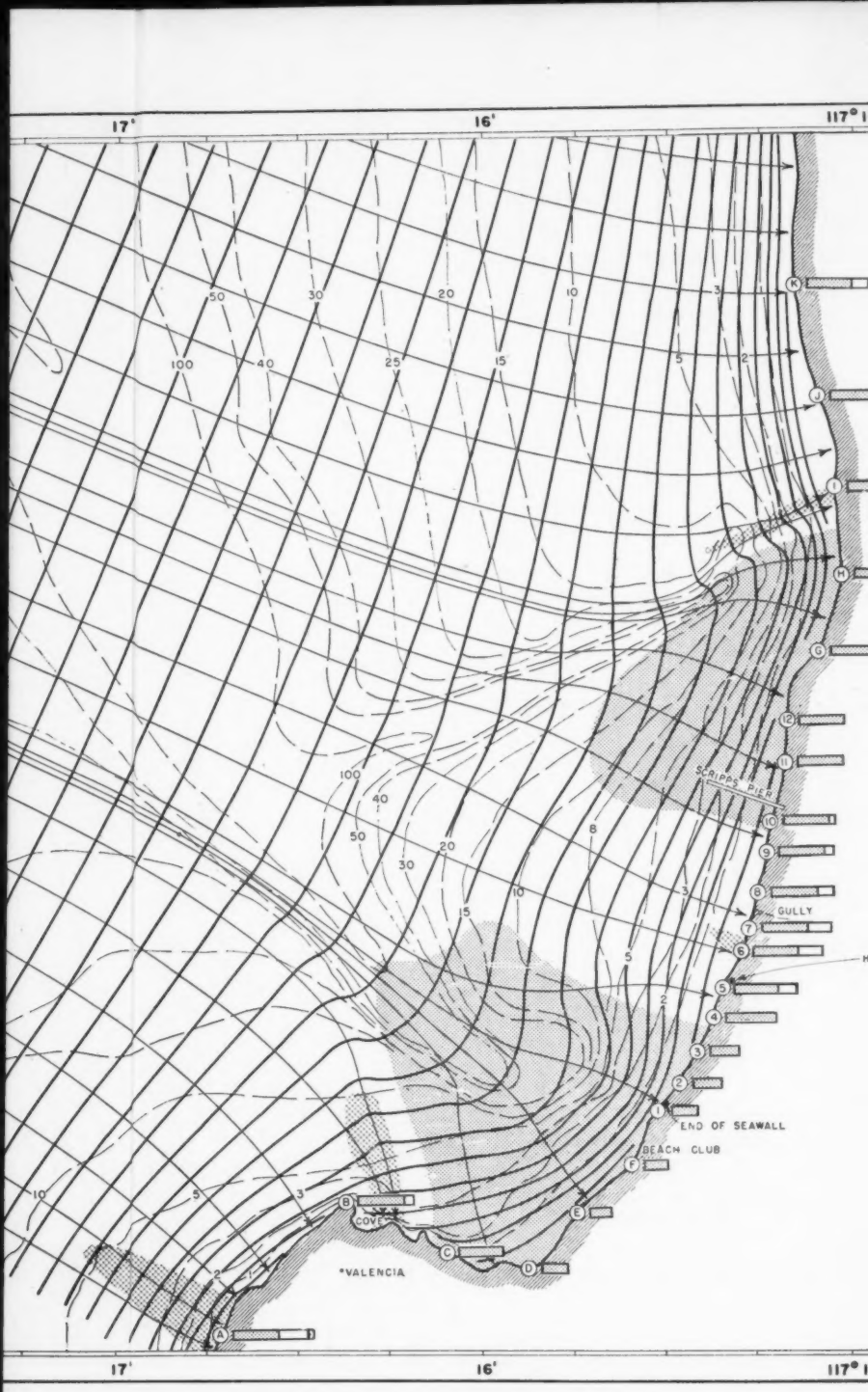
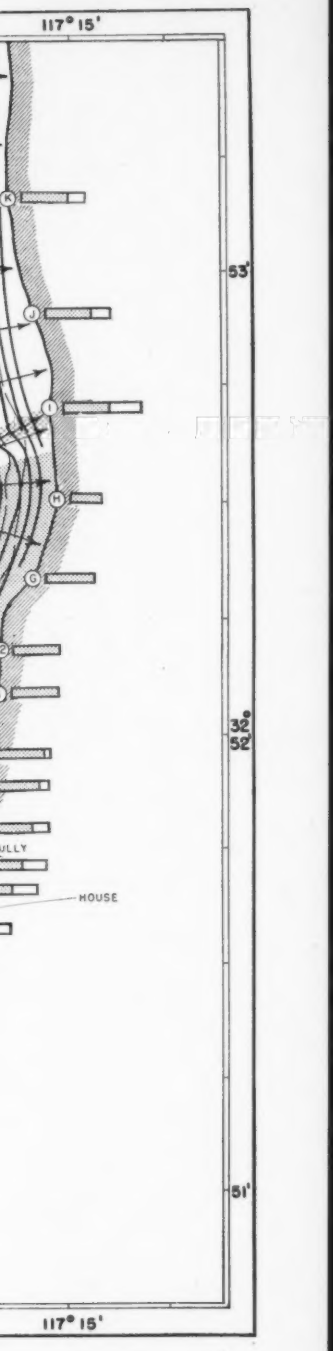
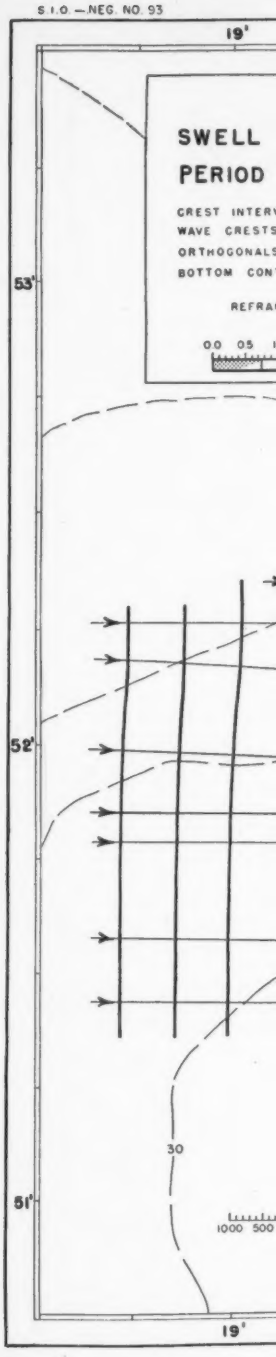


FIG. 9.—The general refraction pattern is similar to the one in Fig. 8 but, ow



n Fig. 8 but, owing to the shorter wave period, variations in wave height are smaller


117° 15'
53'
32° 52'
51'
117° 15'
HOUSE


S.I.O.—NEG. NO. 93
19'
SWELL
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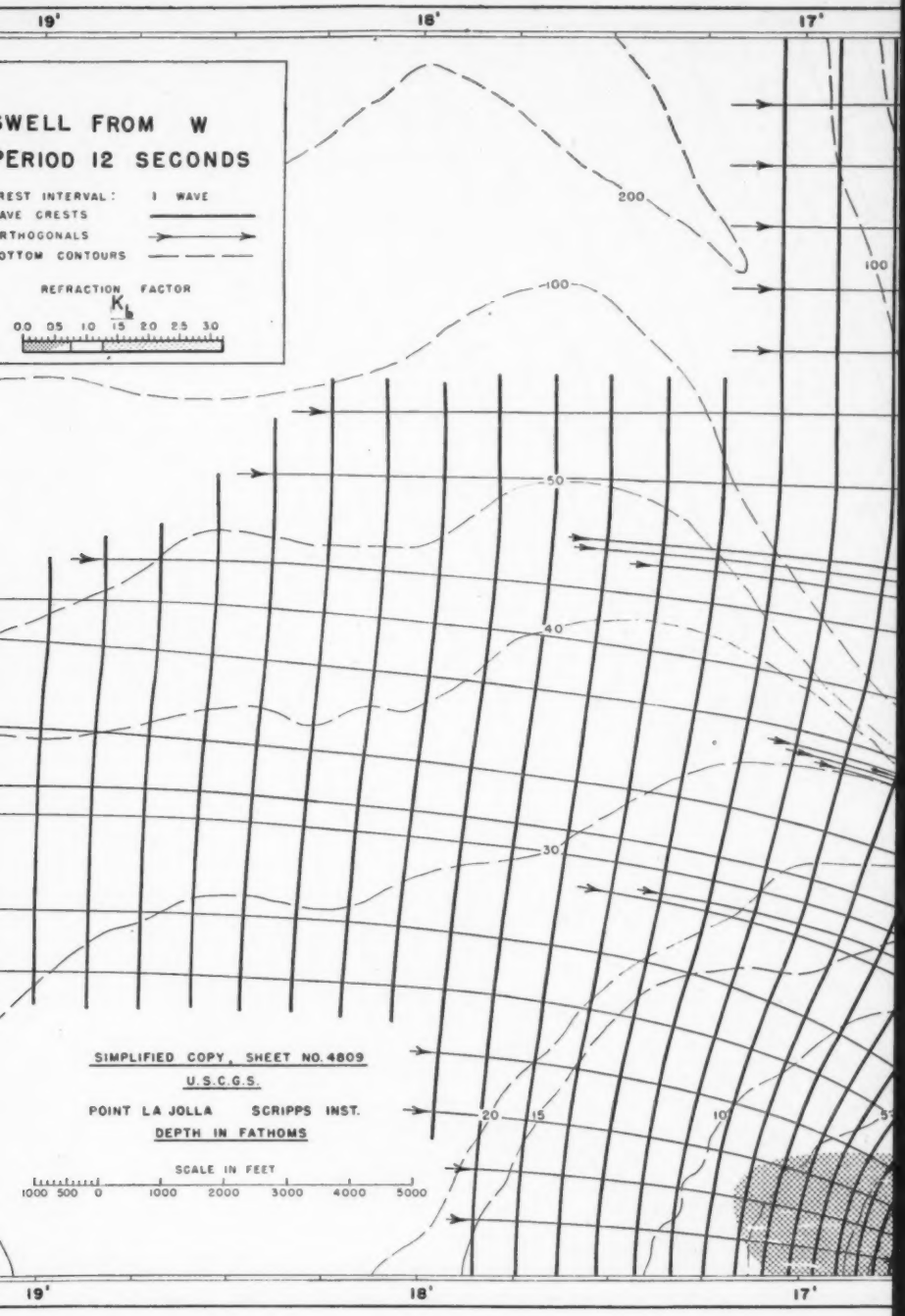
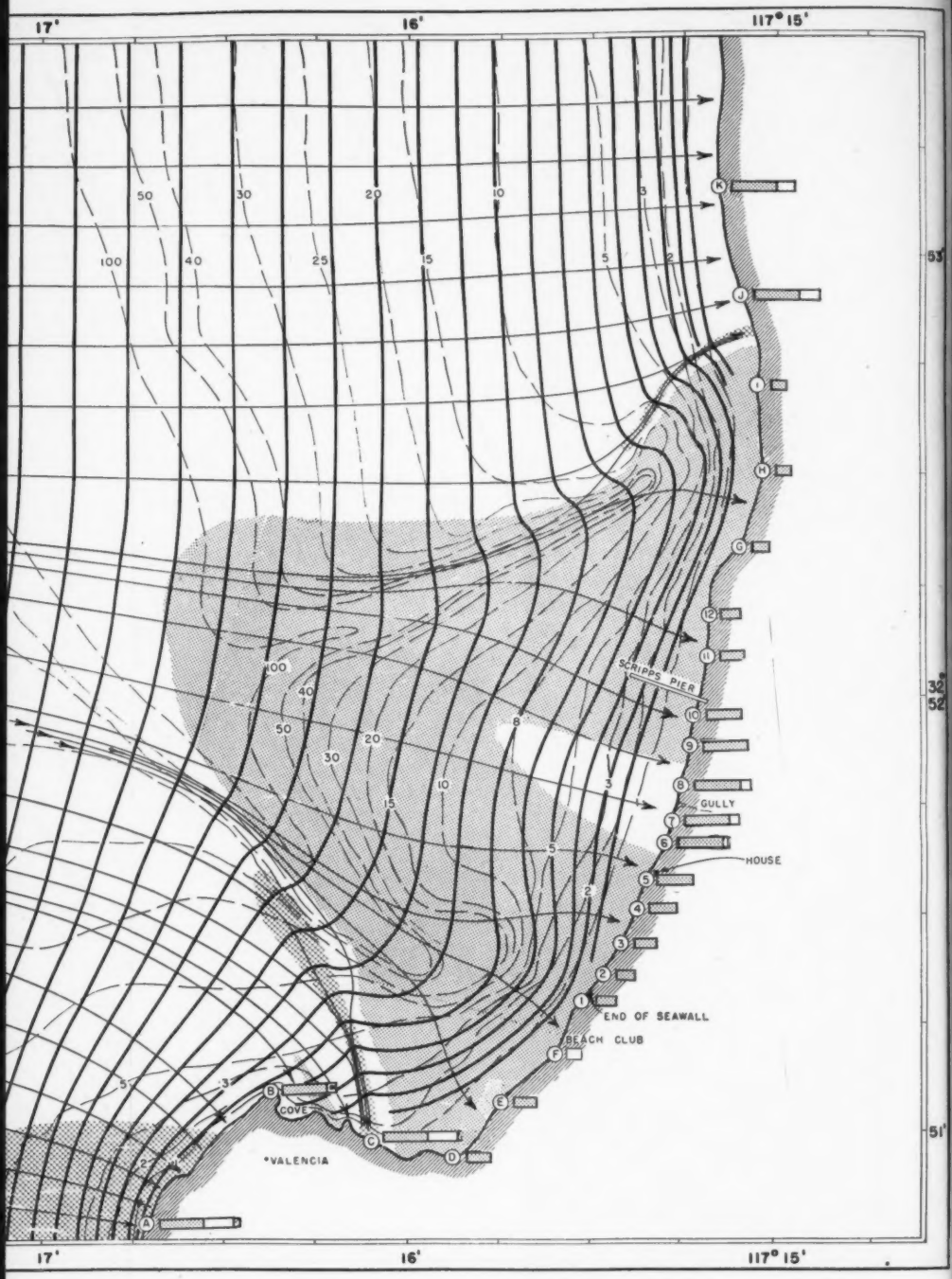


FIG. 10.—Similar to Fig. 9, but, since the waves are assumed to come from the west rather than from th



her than from the west-northwest, the entire refraction pattern is rotated counterclockwise

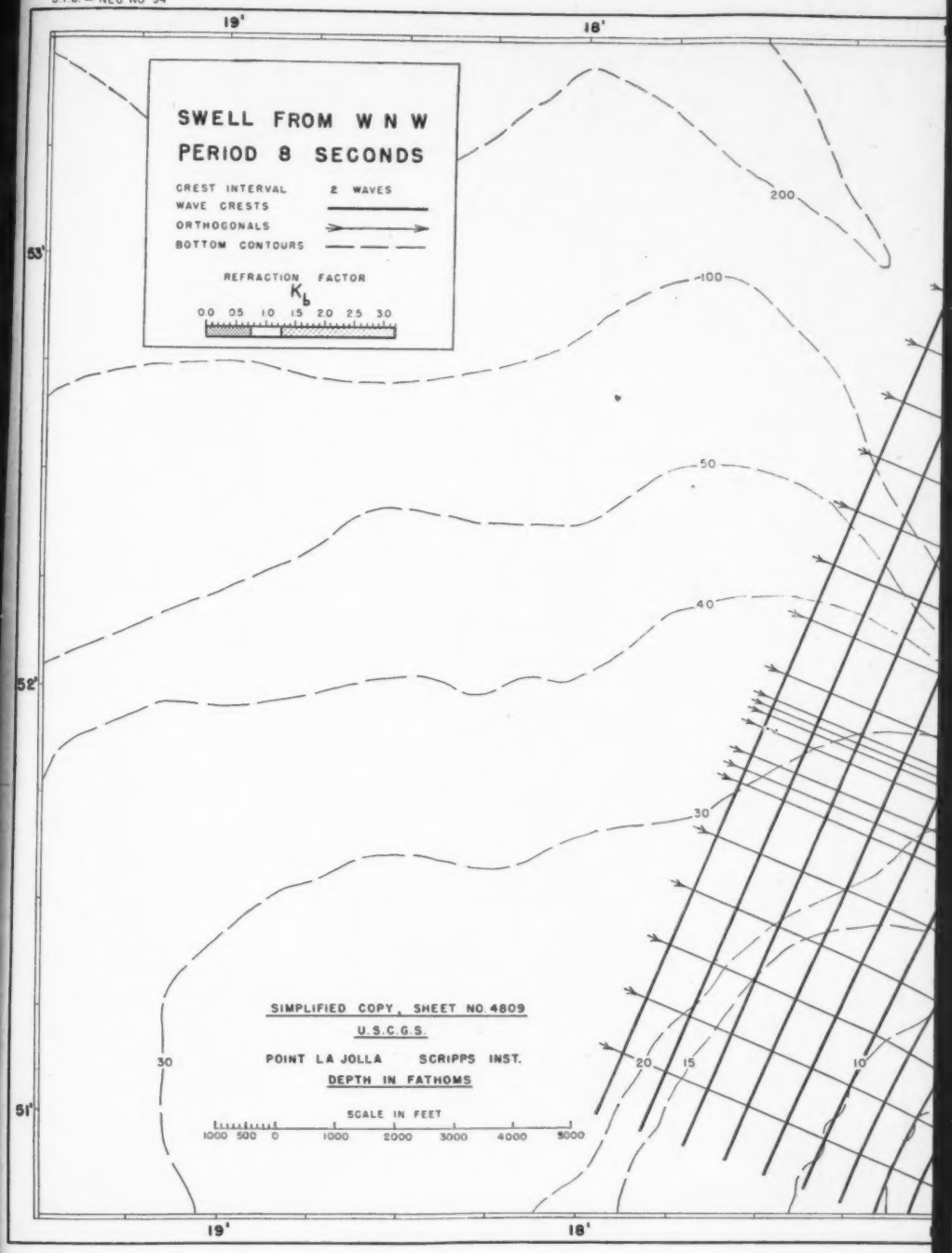
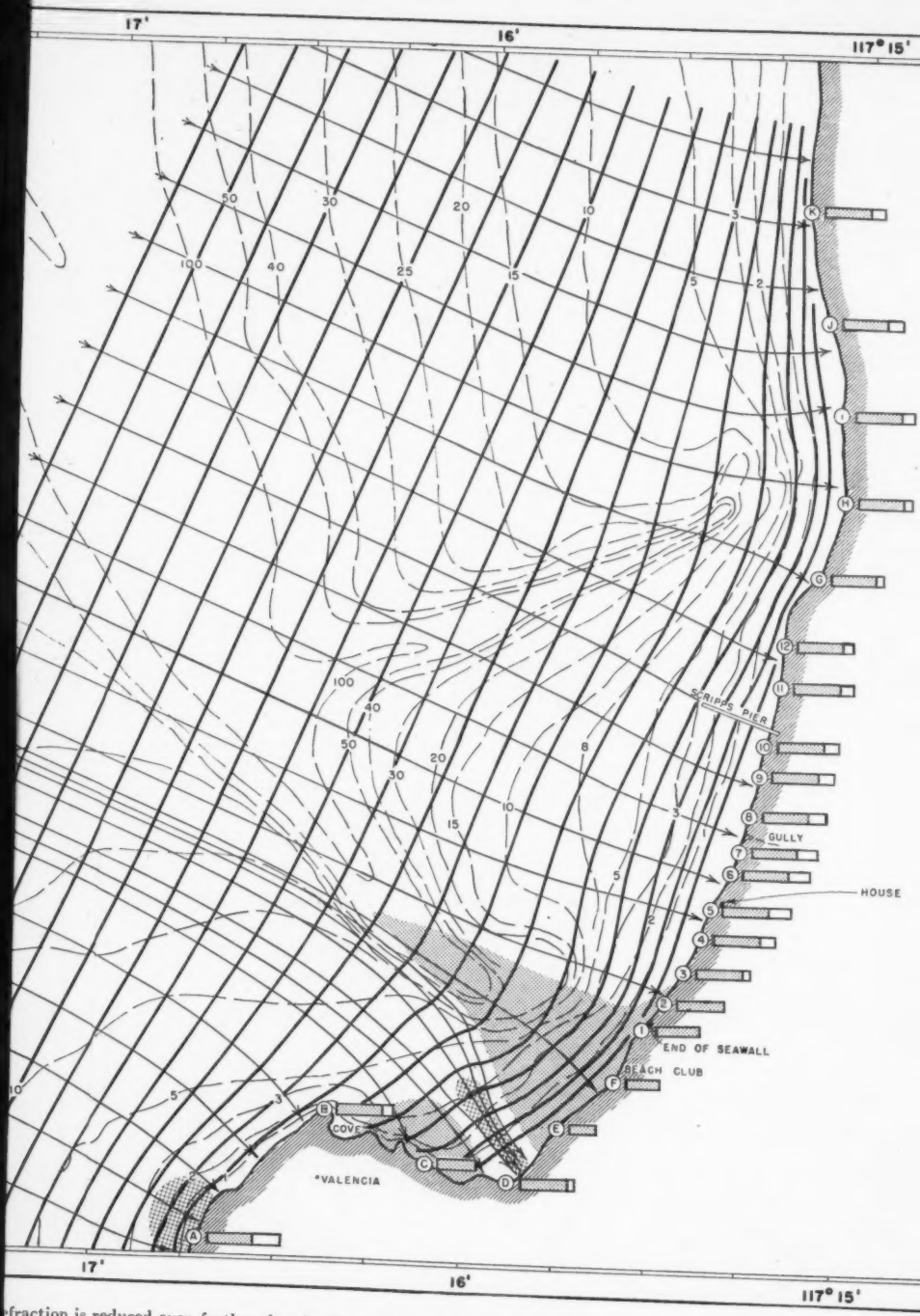
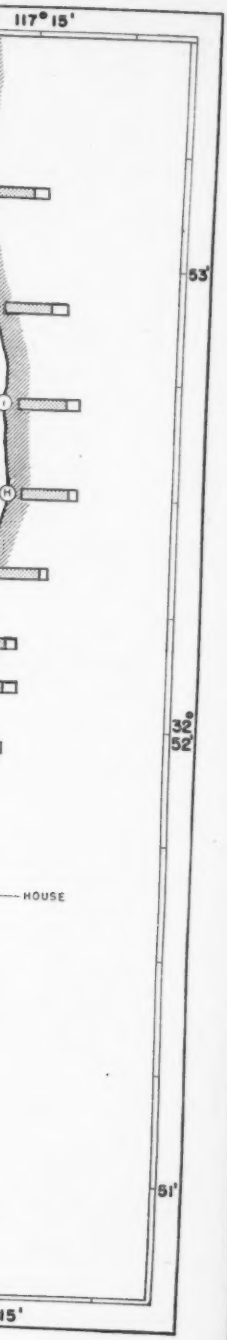


FIG. 11.—Owing to the short wave period, the effect of refraction is



efraction is reduced even further than in the previous refraction diagrams


117° 15'
53'
32° 52'
HOUSE
51'
15'

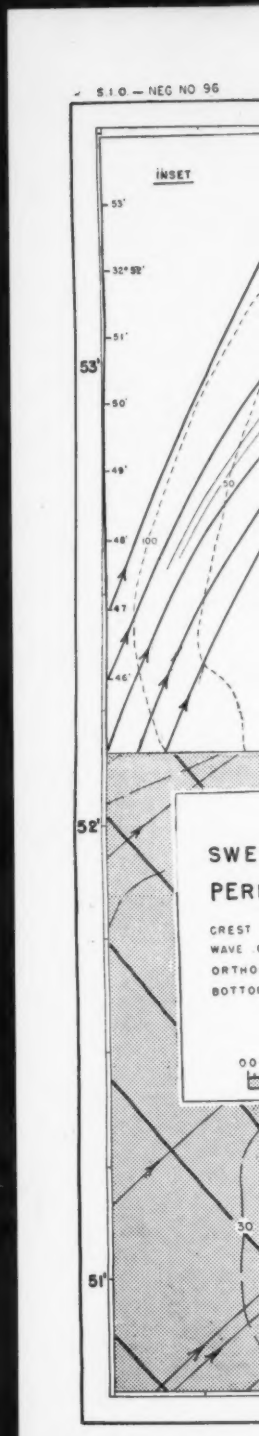
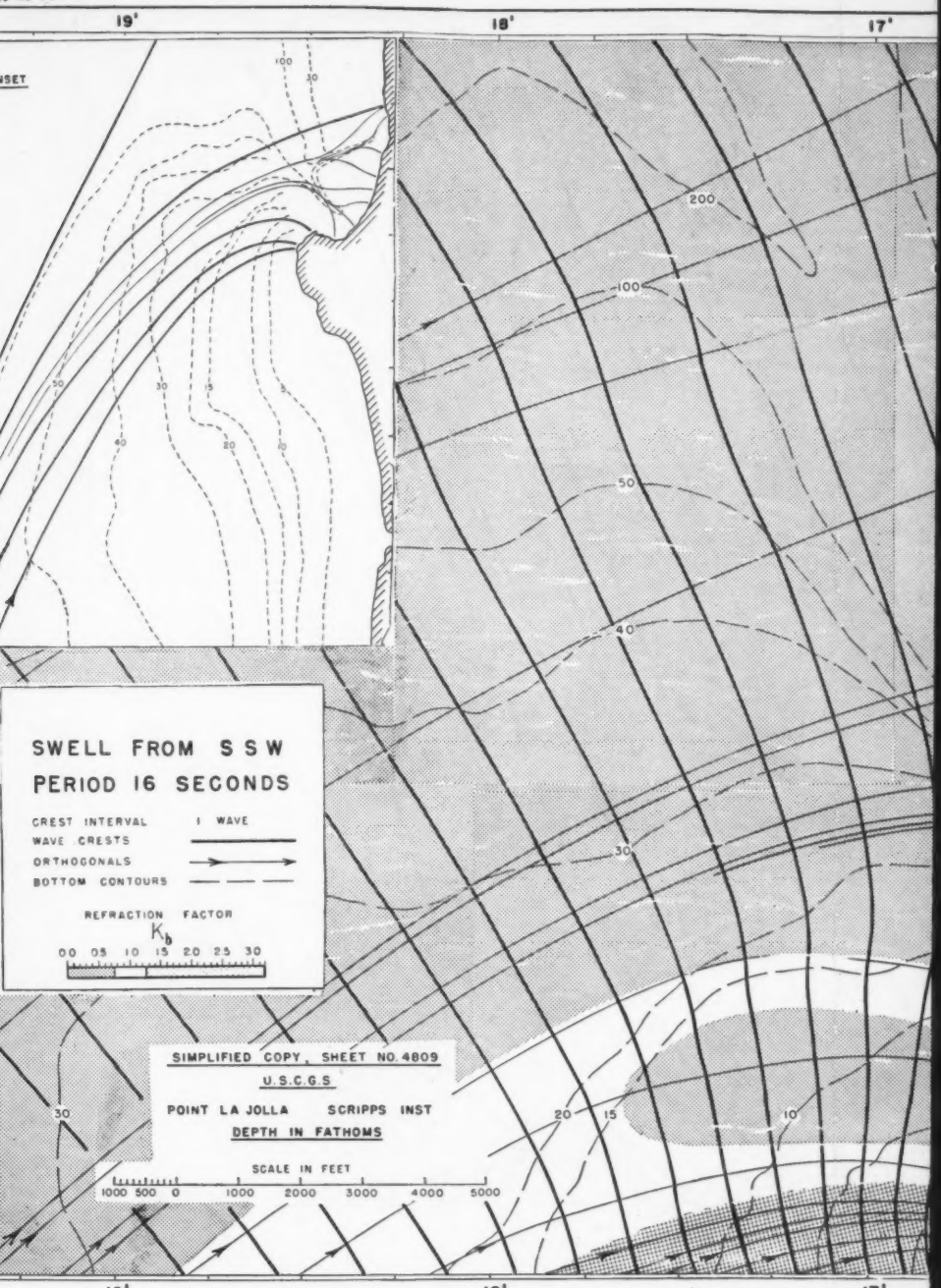
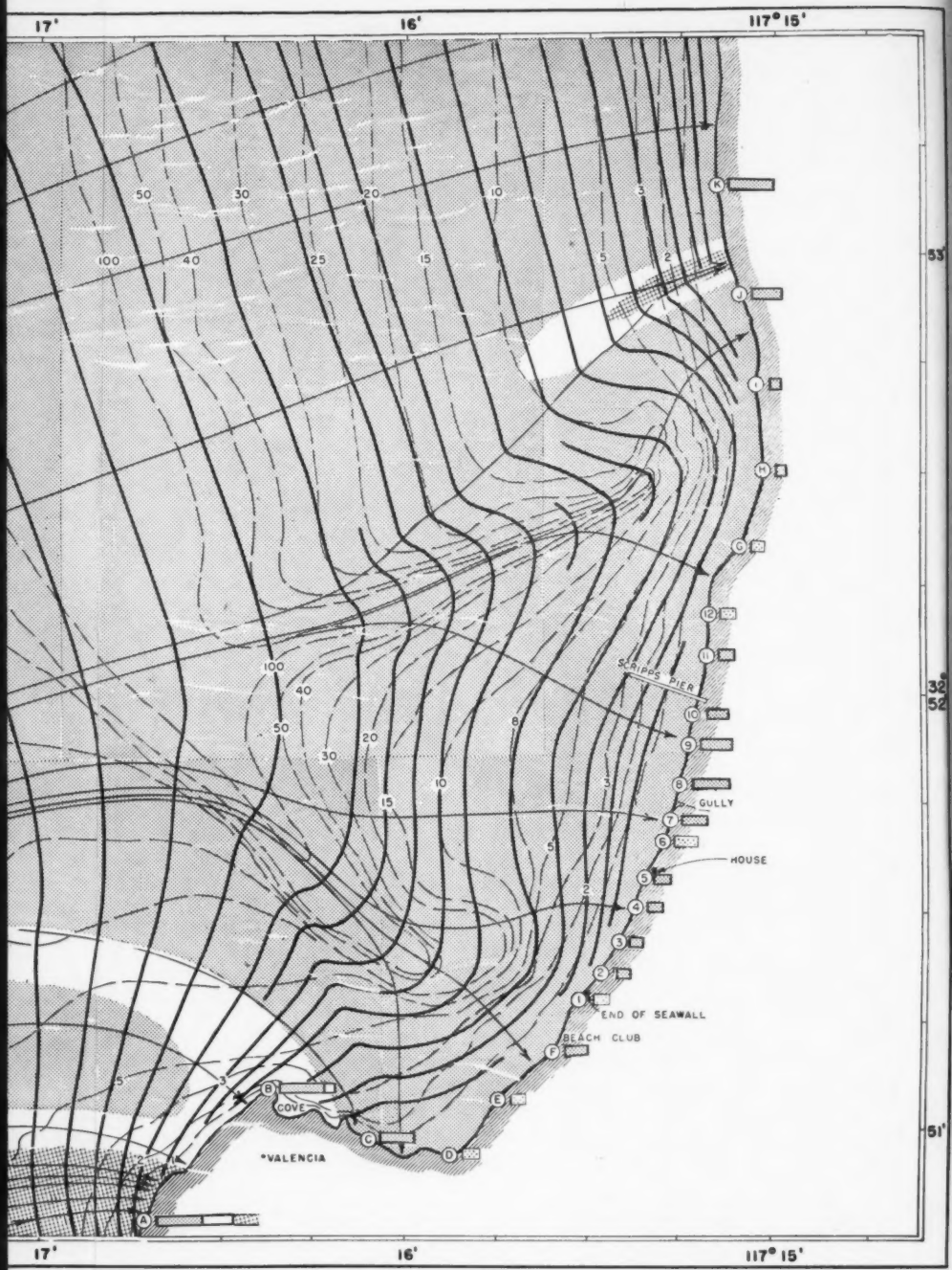


FIG. 12.—Except f
waves from the SSW



Except for two localities near Stations A and J, the entire area is protected from the southern swell. A few selected
he SSW the effect of refraction outside the limits of the main figure cannot be neglected.



few selected orthogonals between deep water and shore have been entered in an inset in order to show that for 16-second

The thin dashed lines on the figures are bottom contours in fathoms; the heavy solid lines are wave crests; and the light solid lines with arrowheads are orthogonals drawn at arbitrary intervals. For waves with periods more than 10 seconds every single crest has been drawn; for waves with periods less than 10 seconds only every second crest has been drawn.

The area offshore has been divided into divergent, normal, and convergent zones, according to whether the refraction factor K (eq. [3*a*]) is less than 0.75, 0.75–1.25 inclusive, or larger than 1.25. Divergent zones are dotted, convergent zones crosshatched, and normal zones left blank.

The value of K_b (eq. [3*b*]) at various stations is proportional to the length of the rectangles at those stations and can be read off from the scale given in the legend of each refraction diagram. In order to emphasize changes in K_b, the columns have been shaded in the same manner used for the offshore area. Columns *ending* in a dotted section designate divergence (K_b less than 0.75); those ending in a crosshatched section designate convergence (K_b larger than 1.25). It should be kept in mind that values of K are proportional to the square root and values of K_b to the cube root of the relative spacing of the orthogonals. The stations where observations were made are numbered *1–12*. Other stations, designated by the letters *A–K*, have been selected because of their representative location.

Waves from WNW, period 14 seconds (Fig. 8).—A small region of relatively high waves, or convergence, is found just north of Station A. An area of intense convergence, which extends approximately northward from the Cove (Station B), is caused by the steep south wall of La Jolla Canyon. This wall is particularly effective because it lies parallel to the direction of wave travel for half a mile. The prolonged effect of the steep bottom slope caused the waves to turn sharply to the right and converge into the Cove. This probably explains the occurrence of unusually high waves at the Cove on days when waves are low along other sectors of the beach. It is well known in La Jolla that these high waves, on days when they occur, come into the Cove at intervals of 15 minutes to several hours. Perhaps the effect of La Jolla Canyon is particularly marked for certain critical combinations of wave period and direction. Although both period and direction are nearly constant for any wave train, they do show continual small variations, and certain combinations of these periods and directions may be the cause of intermittent high waves at the Cove.

The submarine canyon offers protection along the beach from Station C to Station 5 by creating a divergence. This divergence is particularly marked in the vicinity of the Beach Club, where K_b equals 0.3. A slight convergence in the vicinity of Station 6 is the result of waves turned left by the north bank of La Jolla Canyon and is analogous to the convergence near the Cove, caused by the south bank of the canyon. The divergence between Stations 8 and I is caused by the Scripps Canyon. It is less intense than the divergence due to the La Jolla Canyon because for the direction assumed waves do not travel in a line parallel to the walls of the Scripps Canyon. To the north of the Scripps Canyon, between Stations I and J, a small but sharp convergence is found.

The variation of K_b along the beach is also shown in Figure 15. The lower portion of the figure gives the location of the stations and the two submarine canyons.

The upper figure contains a curve for K_b for each of the refraction diagrams. Low wave heights near the head of the two canyons and high waves to either side are clearly shown.

Waves from WNW, period 12 seconds (Fig. 9).—The general features are similar to those caused by the 14-second WNW waves, but the divergence is less intense and covers a smaller area. Wave heights between the two submarine canyons (Stations 4–9) are relatively higher than for the 14-second wave. This difference is chiefly due to the fact that the 12-second wave is shorter than the 14-second wave and that canyons and other bottom features do not affect the 12-second waves to the same degree that they affect the 14-second waves.

Waves from W, period 12 seconds (Fig. 10).—The main features are similar to the ones already discussed, except that regions of divergence and convergence have been shifted due to the difference of wave direction. Thus the convergence on the south edge of La Jolla Canyon has shifted from the Cove to Station C, and the convergence between the canyons from Station 6 to Station 8. The convergence near Station A is more pronounced than for a west-northwesterly swell. Scripps Canyon gives rise to more extreme divergence between Stations 11 and 1 because the direction of wave travel in deep water is more nearly parallel to the walls of the canyon.

Waves from WNW, period 8 seconds (Fig. 11).—The length of these waves in deep water is only one-third that of the 14-second swell, and the effect of refraction is reduced even more than it was for the 12-second waves. In particular, regions of divergence have become much smaller, and only about 3,000 feet of beach are protected by the La Jolla Canyon. The region of divergence opposite the Scripps Canyon has disappeared altogether. The convergence on the south side of La Jolla Canyon has moved to Station D, thus eliminating the cause of relatively high waves at or near the Cove. Nevertheless, it can be seen from Figure 15 that the refraction pattern typical of a submarine canyon has not disappeared: waves are relatively low opposite the mouth of the canyons and high on either side.

Waves from SSW, period 16 seconds (Fig. 12).—A few selected orthogonals between deep water and shore have been entered in an inset on a smaller scale in order to show that for this particular case the effect of refraction outside the limits of the main figure cannot be neglected. By far the larger portion of Figure 12 shows values of K less than 0.75. This divergence is due to the shoal area off Point La Jolla. At only two localities in the vicinity of La Jolla can a convergence of a southern swell be found, opposite the Casa de Mañana Hotel (Station A) and to the north between Stations J and K. A divergence followed by a convergence is caused by the ridge between the submarine canyons. It is believed that this explains the occasional occurrence of relatively high, long-period waves between Stations 7 and 9 during the summer. The refraction diagram explains also why, during the summer, waves are relatively low at the Scripps Institution while they are high at localities with southern exposure, such as near Oceanside and the Coronado Strand.

OTHER METHODS OF PRESENTING REFRACTION DIAGRAMS

If an intensive study is made of a given locality, it may be of advantage to construct a single graph from which the refraction factor K_b and the breaker

angle α_b can be read off directly. In general, K_b and α_b depend upon three variables—the wave direction in deep water, the wave period, and the depth of breaking—but K_b and α_b vary slowly with the depth of breaking, and an average value for the breaking depth may be introduced.

A convenient form of presentation is a polar-coordinate graph with its center placed on an outline map at the position to which the graph applies (Fig. 13). The radial lines give the direction from which the waves come in deep water; the circles give the wave period. The solid curves are lines of equal K_b, the dashed curves lines of equal α_b. The "L = LEFT" and "R = RIGHT" refer to an observer on the beach looking straight out to sea.

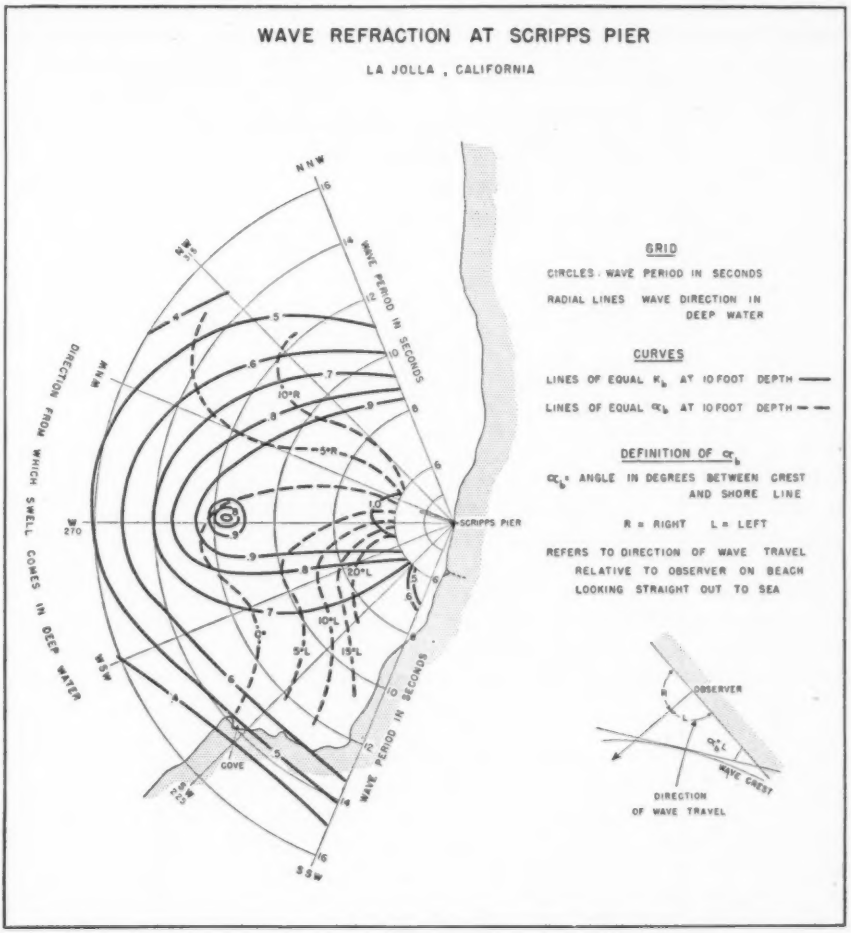

WAVE REFRACTION AT SCRIPPS PIER
LA JOLLA, CALIFORNIA
NNW
WNW
W 270
WSW
SSW
DIRECTION FROM WHICH SWELL COMES IN DEEP WATER
WAVE PERIOD IN SECONDS
SCRIPPS PIER
COVE
GRID
CIRCLES: WAVE PERIOD IN SECONDS
RADIAL LINES: WAVE DIRECTION IN DEEP WATER
CURVES
LINES OF EQUAL K_b AT 10 FOOT DEPTH
LINES OF EQUAL α_b AT 10 FOOT DEPTH
DEFINITION OF α_b
α_b = ANGLE IN DEGREES BETWEEN CREST AND SHORE LINE
R = RIGHT L = LEFT
REFERS TO DIRECTION OF WAVE TRAVEL RELATIVE TO OBSERVER ON BEACH LOOKING STRAIGHT OUT TO SEA
OBSERVER
WAVE CREST
DIRECTION OF WAVE TRAVEL

FIG. 13.—Values of K_b and α_b at a depth of 10 feet along Scripps Institution pier. The polar-coordinate presentation brings out the relative protection of the designated location from the waves coming from SSW to WSW, and the relative exposure to waves from the west.

Figure 13 is drawn for an assumed breaking depth of 10 feet along the Scripps Institution pier. The figure applies with good approximations to breakers anywhere between shore and a depth of 20 feet. The curves were drawn by interpolating between values read off Figures 8–12 and a number of other refraction diagrams drawn specially for the region in the immediate vicinity of the pier. The curve $\alpha_b = 0$ refers to breakers coming straight into shore, that is, from a WNW direction. The other dashed curves are drawn relative to this direction.

Figure 14 applies to the case of a beach with straight and parallel depth contours but is otherwise analogous to Figure 13. For this idealized case the curves for K_b and α_b are given analytically by equations (1) and (5b). From a comparison between Figures 13 and 14, and assuming $T = 14$ seconds, the special effects of the bottom topography and of the con-

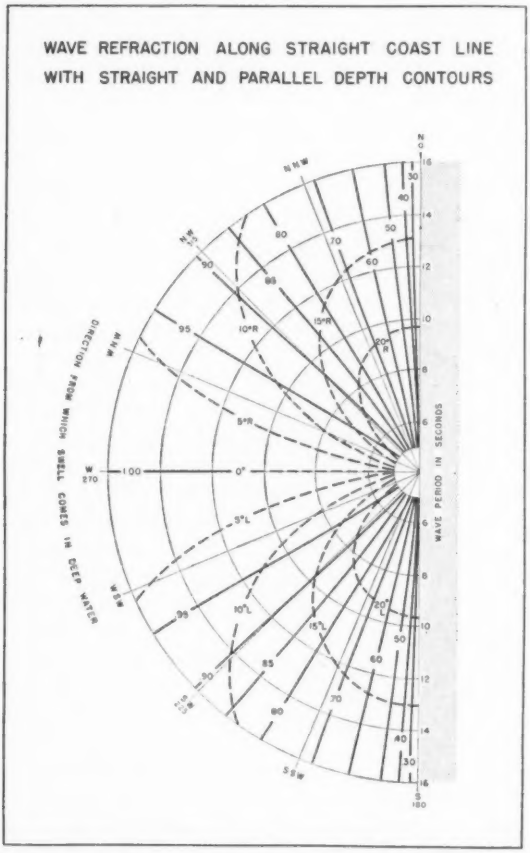


FIG. 14.—Values of K and α_b at a depth of 10 feet for a beach with straight and parallel depth contours (eqs. [1] and [5b]). The special effect of the coastline and the bottom topography at La Jolla can be estimated from a comparison between Figs. 13 and 14.

figuration of the coastline upon the breakers near the Scripps pier can be evaluated (Table 3).

Thus the beach along the pier is particularly well sheltered from southerly waves due to the protection afforded by Point La Jolla and is most exposed to waves directly from the west. This type of presentation gives, therefore, an over-all picture of the protection from, or the exposure to, waves of various directions and periods. The disadvantage of this presentation is that it is limited to a relatively small area. If the emphasis is to be placed upon the changes in wave characteristics along a beach for a given wave situation, the presentation shown in Figure 15 will be more practical.

TABLE 3

	Fig.	Direction from Which Waves Come in Deep Water					
		SSW	SW	WSW	W	WNW	NW
Refraction factor K_b....	13	0.51	0.45	0.57	0.70	0.60	0.45
	14	0.72	0.90	0.97	1.00	0.97	0.90
Breaker angle α_b.....	13	.....	2°L	1°R	2°R	4°R	7°R
	14	13°L	10°L	4°L	0°	4°L	10°L

OBSERVATIONS

Naval officers under instruction at the Scripps Institution, after having been trained for one week in a uniform procedure of observing waves, occupied Stations 1–12 along the beach and made simultaneous observations for 15 minutes. These observations were averaged to obtain observed values. To minimize differences due to personal judgment, observers were shifted regularly from one station to another. From about seventy complete sets of observations, 7 days were selected during which the swell period was well defined and in agreement with forecasts. According to forecasts, all these waves came from WNW. Observations are summarized in Table 4. For each of the twelve stations Table 4 gives the height of the breakers in feet, the height of the breakers as percentage of the average for all stations, and the wave period in seconds. The value for H_b at Station 6 on January 5 appears to be too high, but otherwise observations are fairly consistent.

For each *station* observations made on the 7 days under consideration were averaged and entered in the last column of Table 4. For each *day* observations made at the twelve stations were averaged and entered at the bottom of the table, together with the forecast values. On the 7 days under consideration the average periods vary between 11.5 and 13.8 seconds. The over-all average for observed periods is 12.5 seconds, and for the forecast periods 14 seconds. The forecast direction is WNW. Figures 8 and 9 should therefore apply in all seven cases.

COMPARISON OF THEORY AND OBSERVATIONS

The *computed* refraction factor K_b for waves of 14- and 12-second periods from the WNW was read off at each of the twelve stations. In the case of the 14-second wave, the average value for all stations was 0.62; in the case of the 12-second wave, 0.82. At each station the

individual values of K_b were then expressed as percentages of these average values and plotted in Figure 16 (solid and dashed curves).

The dots in Figure 16 give the average *observed* breaker height and the crosses the average *observed* wave periods, both expressed as percentages of the

lated to a shifting sand bank about 2,500 feet south of the pier.

According to theory, the wave periods should remain constant. Observations plotted in Figure 16 show that this is nearly the case, the lowest value being 95, and the highest 105, per cent of the average. It happens that these small

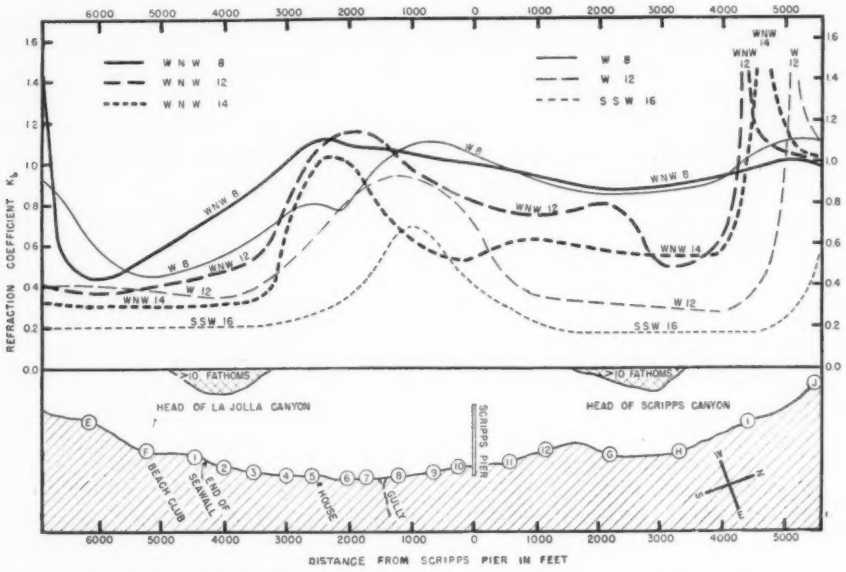


FIG. 15.—Variations of K_b along the coastline according to the refraction diagrams. The lower section of the figure shows the locations along the beach to which values of K_b in the upper section refer. For all but the southern swell, waves are generally lower near the head of the canyon than on either side. Short wave periods give smaller variations in wave height than longer periods. Changes in wave direction shift the location of the zones of convergence and divergence, but they have little effect upon the amplitude of the variation in K_b.

over-all average for all days and stations. These values were taken from the last column of Table 4. In view of the inaccuracies of the observations and the difficulty in drawing exact refraction diagrams, the agreement between theory and observation is satisfactory. The only noticeable discrepancy occurs near Station 7, where the computed wave height exceeds the observed height by about 10 per cent. This discrepancy may be re-

variations in period are in phase with the variations in wave height.

The refraction diagrams can also be compared directly to aerial photographs. Plate VII was selected for an example, because it shows an unusually regular, well-defined swell. The area covered in the photograph extends between Station 5 and Station G.

The swell shown on the photograph was generated in a low-pressure area

TABLE 4

Observations of Breaker Height and Period

Sta. No.	Dec. 1, 1944			Dec. 8, 1944			Jan. 2, 1945			Jan. 3, 1945			Jan. 5, 1945			Feb. 13, 1945			Feb. 14, 1945			Per Cent Averages	
	H_b		T (Sec.)	H_b		T (Sec.)	H_b		T (Sec.)	H_b		T (Sec.)	H_b		T (Sec.)	H_b		T (Sec.)	H_b		T (Sec.)	H_b	T
	Ft.	%		Ft.	%		Ft.	%		Ft.	%		Ft.	%		Ft.	%		Ft.	%			
1	0.7	33	11.5	2.0	38	11	1.0	45	.....	1.0	34	14.0	1.0	22	12.0	3.0	75	12.0	1.5	50	10.0	42	95
2	1.3	62	12.0	2.0	38	11	1.0	45	14.5	1.0	34	11.0	1.5	33	14.0	2.5	63	12.0	2.0	67	9.0	49	94
3	1.5	71	12.0	.....	.....	.....	2.5	114	12.0	1.5	52	13.5	2.0	44	14.0	1.8	45	14.0	3.0	100	12.0	71	102
4	1.5	71	12.0	5.5	104	12	2.5	114	14.0	3.5	121	11.0	4.0	87	12.0	5.0	125	12.0	3.0	100	12.0	103	97
5	2.5	119	13.0	6.0	113	12	3.0	137	14.0	5.0	173	14.0	6.0	130	14.5	6.0	150	13.0	4.0	133	12.0	136	105
6	3.5	167	12.0	4.5	85	12	3.5	159	14.5	4.0	138	14.0	11.0	240	10.0	4.5	113	12.0	4.0	133	11.0	148	103
7	3.5	167	12.0	5.0	94	13	2.5	114	14.0	4.0	138	15.0	5.0	109	15.0	5.0	125	12.0	3.5	117	11.0	123	104
8	3.0	143	12.0	6.0	113	12	2.0	91	13.0	2.5	86	10.0	4.5	98	13.0	4.0	100	12.5	3.5	117	14.0	107	99
9	2.5	119	13.0	6.5	123	13	2.5	114	13.0	3.5	121	11.0	4.5	98	13.0	3.5	88	11.5	3.5	117	11.5	111	98
10	1.5	71	13.0	8.0	151	10	.....	.....	.....	3.5	121	12.0	.....	.....	.....	4.0	100	11.5	3.0	100	11.0	100	95
11	1.5	71	13.0	6.5	123	11	2.0	91	14.0	2.5	86	12.0	5.0	109	12.0	4.0	100	12.0	3.0	100	13.0	97	99
12	.....	.....	.....	6.0	113	13	2.0	91	14.5	2.5	86	14.0	6.0	130	14.0	5.0	125	12.0	2.5	83	11.0	105	103
Av.	2.1	100	12.2	5.3	100	11.7	2.2	100	13.8	2.9	100	12.8	4.6	100	13.6	4.0	100	12.2	3.0	100	11.5	100	12.5
Forecast	3.6	(WNW)	13.0	5.8	(WNW)	12.0	2.0	(WNW)	14.0	2.4	(WNW)	15.0	3.0	(WNW)	15.0	2.6	(WNW)	14.0	3.8	(WNW)	14.0	.....	14.0

1,700 miles WNW of San Diego. The wind blew at 35 knots over a fetch of 800 miles. This situation persisted without much change from May 1 to May 3, 1944. Applying the forecasting method,[14] one obtains 6-foot breakers of 15.5-second period near the Scripps Institution pier at the time the photograph was taken. The height and period, computed from the photograph according to the method given in the surf forecasting manual,[15] equal 7 feet and 14 seconds, respectively. The breaker characteristics computed from weather maps agree with those obtained from the photograph, and the refraction diagram for 14-second waves from the WNW (Fig. 8), should be applicable.

A comparison between Figure 8 and Plate VII shows good agreement between the orientation and spacing of computed and photographed crests. To

[14] "Wind Waves and Swell, Principles in Forecasting," *Hydrographic Office, U.S. Navy, Misc. 11275* (1944). Cf. ftn. 2.

[15] Pp. 42–52 of ftn. 2.

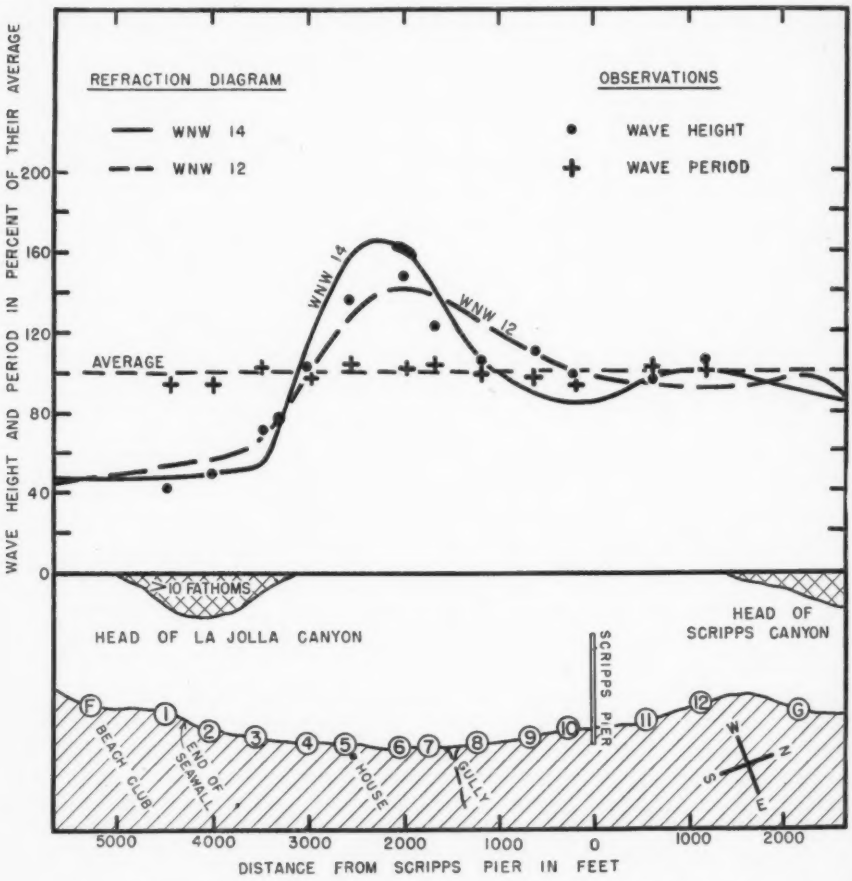


FIG. 16.—Observed versus computed changes in wave height along the beach (see text)

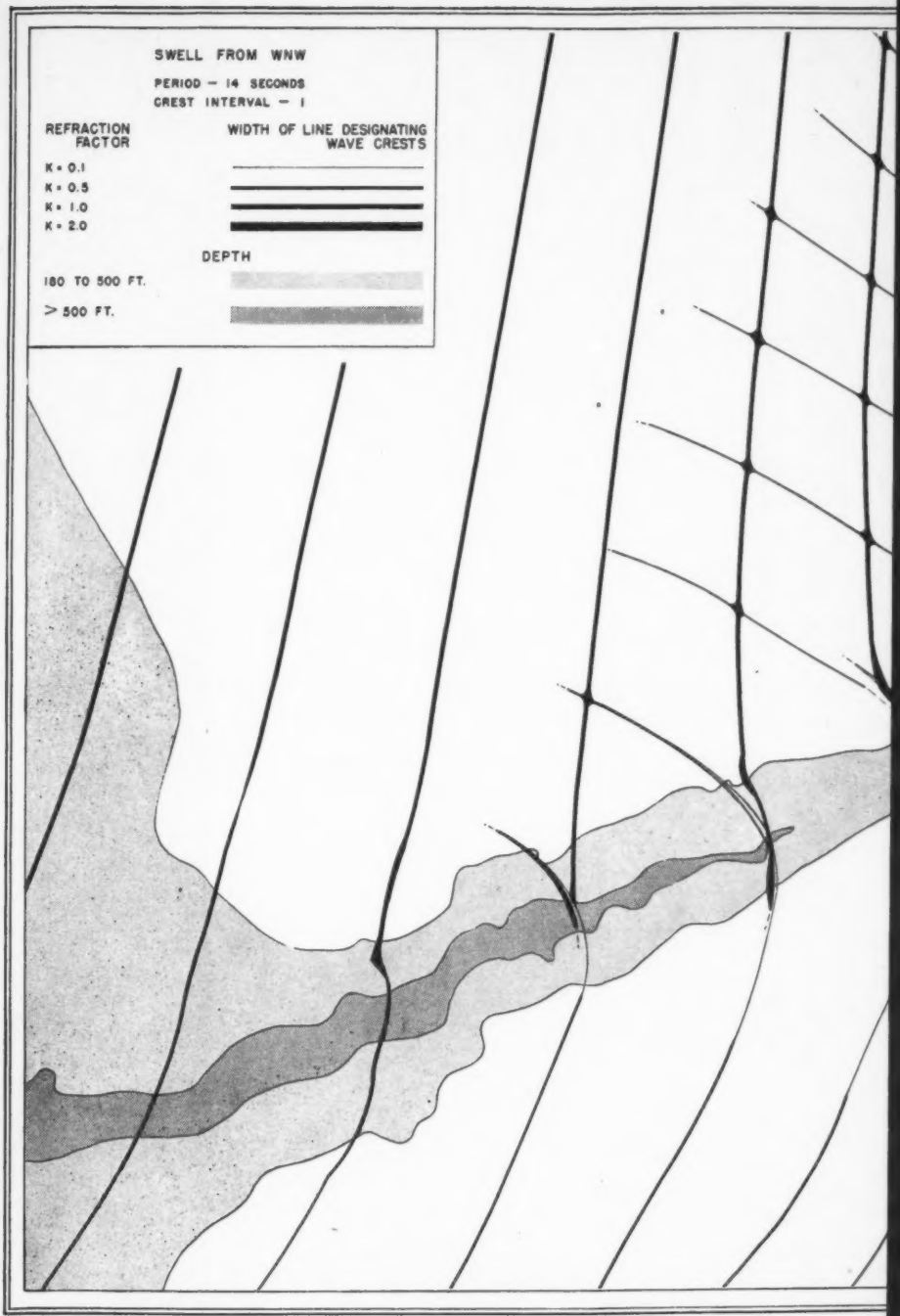
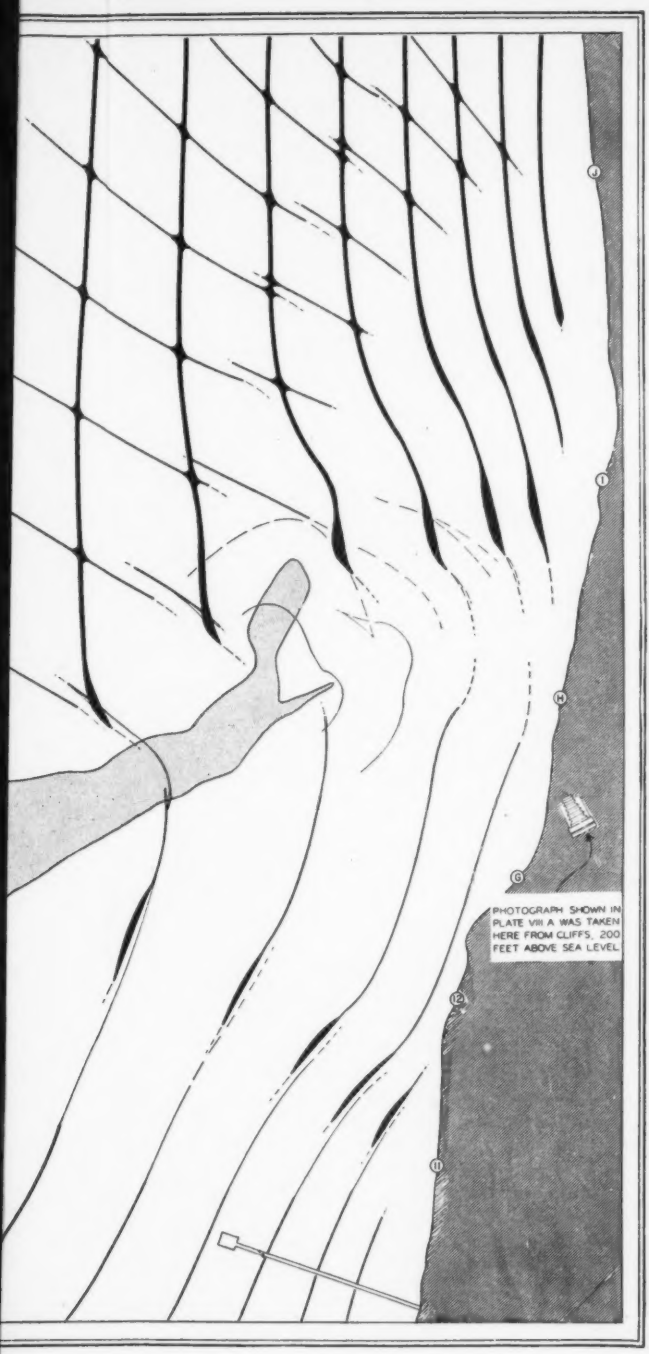


FIG. 17.—Detailed refraction diagram of waves over Scripps Canyon. The shaded areas denote depths exce
and divergence is indicated by the width of the lines designating wave crests. The figure illustrates how
complex pattern.



depths exceeding 180 feet, and 500 feet, respectively. The degree of convergence strates how steep bottom features can break up a simple wave train into a

facilitate the comparison, some of the crests have been transferred from Figure 8 to Plate VII, where they are shown by the inked lines. Near the left edge of Plate VII the photographed crests lag, indicating a shallow bank. On a photograph taken 5 months later a similar lag occurred about 500 feet farther south. This evidence indicates the existence of a shifting sand ridge. The depth contours on Figure 8, which are based on soundings taken prior to 1928, cannot take into account such temporary features. It is quite possible that the discrepancy between observed and computed wave heights near Station 7 is also related to this shifting sand bank.

CROSSING OF WAVE TRAINS NORTH OF SCRIPPS CANYON

At the time the refraction diagrams (Figs. 8–12) were drawn, it was expected that they could give only the basic features regarding the positions of crests and the variations in wave height. Accordingly, small-scale features in the bottom topography and sharp bends in the crests or orthogonals were smoothed out, and the smoothed crest was used as a basis for the construction of the next crest. This crest was also smoothed, when necessary, and this smoothing process was continued from crest to crest as the waves were carried toward shore. In this manner a cumulative error is introduced into the refraction diagram.

If these diagrams are drawn with greater precision, and without smoothing, it is found that the steep walls on the northern side of Scripps Canyon cause a section of the crest to be bent through 90°. This section will travel north along the coast and intersect the regular wave train in a crisscross pattern.

The crisscross pattern is illustrated in Figure 17, which shows a large-scale graph of the refraction of 14-second waves from the WNW over Scripps Canyon between Stations 12 and J. The outermost crest has been transferred from Figure 8. The remaining crests were carried forward with a crest interval of one-eighth the wave period and without smoothing, but only one out of eight computed crest positions is shown on the figure (crest interval = one period). The actual construction of the refraction diagram was carried out on a detailed chart, but only two depth contours are shown on the figure.

It should be kept in mind that the shading in Figure 17 designates bottom topography and not convergence or divergence. In order to picture the degree of divergence or convergence, the *width* of the crest lines has been drawn proportional to the refraction factor K according to the scale in the legend. Wherever the refracted crests intersect the main wave train, a hump on the sea surface is formed, the height of which equals the sum of the height of the two intersecting waves.

Plate VIII, *A*, shows a photograph of this wave pattern, taken from the top of the cliffs at a position indicated on Figure 17. The wave crests in the photograph have been slightly retouched to make them appear more clearly in print. The pattern on the photograph resembles closely the pattern on the refraction diagram.

DISCUSSION AND CONCLUSIONS

METEOROLOGY AND WAVE REFRACTION

In order to draw a refraction diagram, it is necessary to know (1) the wave period and direction in deep water and (2) the bottom topography between deep water and the shoreline. The determination of typical wave periods and deep-water directions for a given locality will

be discussed first, and the bottom topography and its effect will be taken up in the following section.

In the experience of the authors, existing observational data on wave characteristics are almost always inadequate for determining typical deep-water wave directions and periods for a given locality. Data on deep-water wave direction are usually lacking entirely, because they require the services of a boat or a plane. Wave period, since it remains constant, can be measured from shore, but the methods of measuring have been for the most part inconsistent and inadequate.

A better procedure is to obtain the wave characteristics from a knowledge of meteorological conditions and the relationships between wind, sea, and swell.[16] Weather maps are examined to determine all wind areas where waves affecting the locality of interest could be generated. The characteristics of the waves upon reaching the given locality are then computed by the relationships mentioned.

This method has been employed in a study for the United States Navy of the effect of wave conditions upon seaplanes. Meteorologists at the Scripps Institution carried out a day-by-day "forecast" for specified localities on the basis of historical weather maps,[17] the forecasts extending over 3 years. This method required considerable work and highly trained personnel. Fortunately, only a small number of localities have to be considered, since offshore conditions are sufficiently uniform to make the computed wave conditions applicable over long stretches of coastline.

[16] See ftn. 7.

[17] A complete set of Northern Hemisphere weather maps, dating back to 1929, were prepared during the war under the auspices of the Joint Meteorological Committee of the Army, Navy, and Weather Bureau.

The procedure described above consists essentially of computing wave characteristics from *synoptic* weather data and then applying statistical methods to the computed wave data for deriving *climatological* wave conditions. In this report a somewhat less accurate procedure has been followed by making use of average wind data obtained from climatological charts for the different seasons. An exceptionally complete set of wave observations at La Jolla, dating back to 1938, has made it possible to check the soundness of this procedure. Even so, it has been necessary to depend entirely upon local observations for information regarding the southern swell which originates in an area of the South Pacific for which weather data are lacking.

BOTTOM TOPOGRAPHY AND WAVE REFRACTION

Detailed hydrographic charts are required for an accurate construction of refraction diagrams. However, the main features in the refraction pattern can be associated with certain types of underwater topography without the need of elaborate computations (Figs. 1–6 and Pls. I–V). Quite generally it can be shown that the wave refraction pattern for any bottom topography follows a single law, according to which **waves change direction and are bent in such a manner that they *tend* to assume the shape of the depth contours.** Thus the wave crests on an aerial photograph draw a quasi-depth chart. This circumstance has found application during the war in determining underwater topography over enemy beaches.

Associated with the distortion of the waves are local convergences and divergences of wave energy. It is important to make a distinction between an area of *divergence* and what might be called a

complete wave *shadow zone*. Waves behind a headland or to the lee of an island are usually very low because of the divergence of wave energy, yet the protected region does not lie in a wave shadow zone. Indeed, sensitive instruments have shown that waves can reach any section of a coastline, no matter how well protected, unless that section is completely cut off from communication with the open sea. By the time the waves have turned through a large angle, they are usually too low to be noticeable to the naked eye, but in some instances local convergences in so-called protected zones have led to surprising results.[18]

THE CONCEPT OF RELATIVE DEPTH

It should be emphasized that the effect of bottom features upon waves depends not upon the absolute depth of water but upon the *relative depth*, that is, the ratio of depth over deep-water wave length (h/L_0). Let h and L_0 be given in feet, and the wave period T in seconds. Setting $g = 32.2$ ft/sec^2 in Appendix equations (A5*b*) and (A6*a*), one obtains approximately $L_0 = 5\ T^2$, and

$$\text{Relative depth}: \quad \frac{h}{L_0} = \frac{h}{5T^2}. \qquad (6)$$

By definition shallow water has a relative depth of less than one-half. For a long 14-second swell shallow water starts therefore at a depth of 500 feet; for a short 7-second wind wave, at 125 feet. Since modification of waves occurs only in shallow water, a shoal at an average depth of 500 feet would affect the swell in a manner similar to that in which a shoal at 125 feet would affect the short-period sea. An interesting application of this principle is the *separation* of a short-period sea from a long-period swell by special types of bottom features. The bottom topography itself can be compared to an enormous lens, separating waves of different frequencies much as a lens breaks up light into the component colors. A famous illustration of this feature is provided by the surf at Waikiki beach in the Hawaiian Islands, which usually results from a NE swell refracting around Nakapuu Point and Diamond Head. Out at sea a short NE chop will usually be present in addition to the swell, but the chop is too short to be refracted effectively and thus passes on without bending into the beach.

Since ordinary waves rarely have periods much longer than 14 seconds, the effect of underwater bathymetry on these waves is virtually limited to the continental shelf. But sea and swell are not the only waves of the sea refracted by the ocean bottom. Fault movements associated with submarine earthquakes generate very long waves, "tsunamis," popularly called tidal waves (although they are not related to tides), and these have periods ranging between 10 minutes and an hour. In accordance with equation (6), these waves are always in shallow water, even over the deepest portion of the oceans. Preliminary results of an investigation by Shepard and others[19] show a good correlation between the variations

[18] An interesting application of the effect of refraction on wave height was made in connection with the liberation of the Philippine Islands. During the planning stage refraction diagrams were prepared for waves entering the Lingayen Gulf from the north, and they showed a convergence for the landing beaches, but a divergence east of the town of Lingayen. Consequently, an alternate plan was made to provide for the contingency of high waves from a typhoon. Shortly after the initial landings, high breakers prevented unloading at the main beachhead, but the breakers remained low to the east of Lingayen as indicated on the refraction diagram. A second beachhead was established according to the alternate plan, and the unloading of supplies continued without interruption.

[19] G. A. MacDonald, F. P. Shepard, and D. C. Cox, "The Tsunami of April 1, 1946, in the Hawaiian Islands (Preliminary Report)," *Pacific Sci.*, Vol. I No. 1 (January, 1947), pp. 21–37.

in the height of the April, 1946, tsunami in the Hawaiian Islands and the offshore topography and promise an interesting application of the principles discussed in this paper. A similar effect, but of even larger order of magnitude, must result from the refraction of tsunamis by large-scale bathymetric features, such as ocean basins and troughs. This might explain the curious fact that waves of the April, 1946, tsunami were recorded about twice as high at South American stations as they were at stations along California, although they had originated near the Aleutian trough and traveled more than twice as far to the South American stations.

WAVE REFRACTION AND BEACH EROSION

Krumbein[20] in his study of Half Moon Bay, California, was probably the first to consider the effect of wave refraction on sediment transport. He states that a refraction diagram indicated at least the order of change in wave energy along the coast. In the present paper it is shown that refraction diagrams also give this change quantitatively. This conclusion is of particular significance because the unusually complex bottom topography off La Jolla provides a critical test of the application of refraction theory to ocean waves. It also appears that wave refraction can be depended upon to give not only the simple main features regarding wave height and direction but also more complicated secondary effects, such as the crisscross pattern north of Scripps Canyon.

Refraction diagrams, if properly used, can become a powerful tool in the study of beach erosion. Although several processes are involved, two must be of particular importance in the effect of refraction upon beach erosion: (1) transport of sediments by *advection* associated with the secondary current system set up by the waves and (2) transport of sediments by *diffusion* associated with the turbulence set up by the breakers. The former process depends critically upon the *direction* of the waves, the latter upon the variation in *height* of the waves. The two processes depend, therefore, upon the two elements of the refraction pattern.

The term "advection" has been borrowed from meteorology or oceanography, where it denotes a transport due to a current flowing from a region of high concentration to a region of low concentration. Mathematically the effects of diffusion and convection are both contained in the vector equation

$$\frac{\partial s}{\partial t} = \nabla^2 \cdot \mathbf{A} - \nabla \cdot s\mathbf{V}, \qquad (7)$$

where s is any concentration, $\mathbf{A}$ the vector coefficient of kinematic eddy diffusivity, and $\mathbf{V}$, the vector velocity. Equation (7) states that the local time change of any concentration equals the effect of diffusion minus the effect of advection. For further discussion refer to chapter v of Sverdrup *et al.*[21]

Of the currents set up by the waves, the most important are probably longshore currents, or littoral currents, and rip currents.[22] The longshore currents are set up by the transport of waves breaking at an angle with the shoreline. They are directed, therefore, *with* the longshore component of the wave motion—for example, from left to right in Figure 1. In the case of high waves and breakers forming an angle of more than 10° with

[20] "Shore Processes and Beach Characteristics," *Technical Memorandum No. 3, Beach Erosion Board* (May, 1944).

[21] H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, *The Oceans, Their Physics, Chemistry and General Biology* (New York: Prentice-Hall, 1942).

[22] F. P. Shepard, K. O. Emery, and E. C. La Fond, "Rip Currents: A Process of Geological Importance," *Jour. Geol.*, Vol. XLIX, No. 4 (May–June, 1941), pp. 337–69.

the coastline, longshore currents may attain velocities of several knots. If it were not for the fact that breaker angles are greatly reduced by refraction, longshore currents would attain such high velocities that the rate of beach erosion would be many times its actual value.

The refraction pattern for submarine canyons causes the longshore currents to diverge from the center of the canyon toward both sides, leading to a removal of sediment from the canyon head. In the case of submarine ridges, the longshore currents and the sediments converge upon the ridge. Submarine canyons and ridges are associated, therefore, with a refraction pattern which sets up a current system that tends to perpetuate their existence.

Rip currents are directed from shore out to sea. Along a straight coastline they are most pronounced when the waves come straight toward shore. Usually the location of rip currents is closely associated with the refraction pattern. In the case of submarine canyons, rip currents tend to form at the zones of convergence at either side of the canyon, although frequently they turn and flow directly over the canyon just outside the breaker zone. In the case of ridges, rip currents tend to form in the convergence above the ridges. Exceptions to all these rules are, however, frequently found. The effectiveness of rip currents in transporting sand can be gauged by the fact that they have been observed to erode a channel several feet deep within a short time interval.[23]

Transportation of sediments by *diffusion* must result from the variation of wave heights along the beach. Wave heights are low opposite the mouth of the submarine canyons and high on either side. Since high breakers cause a heavy degree of turbulence, and low breakers only little turbulence, sand may be kept in suspension on the sides of the canyons while it has a chance to settle over the canyon. In the case of submarine ridges similar reasoning leads to the conclusion that the ridges tend to be eliminated by diffusion. Thus the effect of diffusion is opposite to the effect of advection. Since it is known that the heads of submarine canyons are kept fairly clean of sediments[24] and that ridges may exist for long times, it appears that the advective processes must balance the effects of diffusion and slumping.

Tidal currents are rarely of much importance along open coastlines exposed to severe wave action. The change in tide level may, however, be important, since it causes a back-and-forth shift of the surf zone, which in turn will have an effect upon the location of longshore currents, rip currents, and the zones of maximum turbulence. The rise and fall of the mean sea-level makes it impossible for any beach ever to reach a state of complete equilibrium.

It should be emphasized that the manner in which sediment is transported by wave action is not properly understood and that many exceptions have been found to the foregoing statements. Conditions, as they exist along a beach at any given time, approach a sensitive balance between erosion and deposition. The balance is profoundly disturbed by any changes in the wave and weather conditions or by the building of jetties and breakwaters. For similar reasons the manner in which the sands along a beach are shifted back and forth by wave action must depend greatly upon the refraction pattern. The resulting sediment transport may cause changes in depth which in turn affect the refraction pat-

[23] *Ibid.*, pp. 350–52.

[24] Shepard and Emery, pp. 94–103 of ftn. 13.

tern (Pl. VIII, *B*). This interplay between waves and bottom makes the prediction of changes in the bottom profiles extremely difficult. But by analyzing the effects of wave action from the point of view of fluid mechanics, making use also of refraction diagrams, it seems likely that a better understanding of the processes involved in beach erosion will result.

Another point of view we have tried to introduce into this report is the importance of meteorology to studies of beach erosion. A season which is unusual from the point of view of beach conditions must, in the final analysis, be the result of unusual meteorological conditions over the ocean. This does not necessarily mean that local weather conditions have been unseasonal. We have noted, for example, that some of the swell reaching southern California in the summer depends upon weather conditions in the Southern Hemisphere, perhaps 5,000 miles away. The ever changing beaches along the shorelines are a reflection of the infinite number of possible combinations and variations of storms over widely spread areas of the ocean.

APPENDIX

THEORY OF WAVE REFRACTION

Let E denote the mean energy per unit surface area, n the fraction of this energy advancing with the wave crest at velocity C, and s the distance between adjacent orthogonals. Then, if energy is conserved between orthogonals,

$$E_0 n_0 C_0 s_0 = EnC s = E_b n_b C_b s_b \,, \quad \text{(A1)}$$

where the subscript "o" refers to deep-water conditions, i.e., water whose depth exceeds one-half the wave length, and the subscript b to the breaker point. The expression without subscripts holds generally in shallow water, intermediary between deep water and the breaking-point.

In deep water the wave energy is proportional to the *square* of the wave height H_o according to the equation

$$E_0 = \tfrac{1}{8} \rho g H_0^2 \,, \quad \text{(A2}a\text{)}$$

where ρ is density and g the acceleration due to gravity. The same relationship holds with good approximation in shallow water:

$$E = \tfrac{1}{8} \rho g H^2 \,. \quad \text{(A2}b\text{)}$$

However, just outside the breaking-point, the shape of the waves approaches that of "solitary waves," with sharp isolated crests, separated by long flat troughs. For solitary waves the wave energy is proportional to the cube of the wave height, according to the equation

$$E_b = \frac{\rho g}{L_b} \left(\frac{4 h_b H_b}{3} \right)^{3/2} . \quad \text{(A2}c\text{)}$$

Combining the first two expressions of equations (A1) and (A2), we get the following general relationship for the wave height in shallow water:

$$\frac{H}{H_0} = \left(\frac{n}{n_0} \frac{C}{C_0} \frac{s}{s_0} \right)^{-1/2} . \quad \text{(A3)}$$

In deep water only half the energy, the potential energy, advances with the wave form:[25]

$$n_0 = \tfrac{1}{2} \,. \quad \text{(A4}a\text{)}$$

In the breaker zone both potential and kinetic energy travel with the waves,

$$n_b = 1 \,, \quad \text{(A4}b\text{)}$$

while for shallow water in general

$$n = \frac{1}{2} \left[1 + \frac{\frac{4\pi h}{L}}{\sinh \left(\frac{4\pi h}{L} \right)} \right] . \quad \text{(A4}c\text{)}$$

Equation (A4c) reduces properly to equations (A4a) or (A4b), depending upon whether the ratio h/L has a large or small value.

The velocity of sinusoidal irrational waves of low amplitude is given by the classical Stokes's equation

$$C^2 = \frac{gL}{2\pi} \tanh \frac{2\pi h}{L} \,, \quad \text{(A5}a\text{)}$$

[25] H. U. Sverdrup and W. H. Munk, "Wind, Sea and Swell: Theory of Relations for Forecasting," *Hydrographic Office, Technical Report in Oceanography No. 1* (in press).

which for deep water reduces to the form

$$C_0^2 = \frac{gL_0}{2\pi}. \qquad (A5b)$$

Since wave period T, defined as the ratio of wave length over wave velocity, remains constant

$$T = \frac{L_0}{C_0} = \frac{L}{C} = \frac{L_b}{C_b} \qquad (A6a)$$

or

$$\frac{C}{C_0} = \frac{L}{L_0}. \qquad (A6b)$$

Dividing (A5a) by (A5b) and making use of (A6b), we get

$$\frac{C}{C_0} = \frac{L}{L_0} = \tanh \frac{2\pi h}{L}. \qquad (A7)$$

Equation (A7) can also be written

$$\frac{L}{L_0} = \tanh \left[2\pi \frac{h}{L_0} \left(\frac{L}{L_0} \right)^{-1} \right], \qquad (A7')$$

which is an equation of the form

$$\frac{L}{L_0} = \text{function} \left(\frac{h}{L_0} \right). \qquad (A8)$$

The ratio h/L_0 is termed "relative depth." It follows from equations (A7) and (A8) that the ratio C/C_0 is a function of the relative depth only. In a similar manner it can be shown that the ratio n/n_0 is a function of the relative depth.

Thus equation (A3), which can be written

$$\frac{H}{H_0} = \left(\frac{n}{n_0} \frac{C}{C_0} \right)^{-1/2} \sqrt{\frac{s_0}{s}}, \qquad (A9)$$

consists of two parts: the first part, which depends upon the relative depth and does not contribute toward a *variation* in wave height along any fixed contour, and the second part, the refraction factor, according to which any variation in wave height along a beach outside the breaker zone, must be proportional to the square root of s_0/s.

To find the corresponding expression for the breakers, combine the first and third term of equations (A1) and (A2)

$$\frac{C_0}{2} \tfrac{1}{8} H_0^2 s_0 = \frac{C_b}{L_b} \left(\frac{4 h_b H_b}{3} \right)^{3/2} s_b,$$

where use has been made of equations (A4a) and (A4b). In view of (A6a), this can be written

$$h_b H_b = \tfrac{3}{4} \left(\tfrac{1}{1.6} \right)^{2/3} (H_0^2 L_0)^{2/3} \left(\frac{s_0}{s_b} \right)^{2/3}. \qquad (A10)$$

According to theory substantiated by experiments with solitary waves,

$$h_b = 1.28 H_b, \qquad (A11)$$

and equation (A10) becomes

$$\frac{H_b}{H_0} = \frac{1}{3.3 \sqrt[3]{\frac{H_0}{L_0}}} \sqrt[3]{\frac{s_0}{s}}. \qquad (A12)$$

Any *variation* in breaker height must be proportional to the cube root of s_0/s. The ratio H_0/L_0 is called the wave steepness in deep water. Equation (A12) and the foregoing discussion hold strictly only for waves of steepness H_0/L_0 less than 1 per cent (i.e., for swell) but is approximately true for all but the steepest storm waves.

The general equation (A9) for wave heights in shallow water neglecting refraction was first derived by Green in 1839 and extended by O'Brien and Mason[26] to include the refraction effect. The existence of solitary waves was first noticed by Russell, and their theory was developed by Boussinesque in his study of tide waves and related phenomena. The application of the solitary-wave theory to surf problems and the derivation of equation (A12) are believed to be new.

ACKNOWLEDGMENTS.—We are indebted to Dr. H. U. Sverdrup for the active role he has played in developing the theory and application of wave refraction. Dr. F. P. Shepard and Mr. D. Leipper have made many helpful suggestions. The exacting job of constructing the refraction diagrams in Figures 8–12 was undertaken by Sgt. R. Jentoft, AC, while on duty at the Scripps Institution. Mr. D. Pritchard has drawn the complex refraction diagram shown in Figure 17.

[26] Pp. 37–39 of ftn. 5.

PLATE I

A, Long waves from the southern hemisphere approaching the coast north of Oceanside, California. Compare refraction pattern with schematic drawing in Fig. 1. (Official photograph, United States Navy.)

B, Refraction of waves over ridge along the northern shore of Oahu, T.H. (cf. Fig. 4). Over the ridge waves lag behind and are higher than on either side. (Official photograph, United States Army.)

PLATE II

Refraction of waves over submarine canyon at Redondo, California (cf. Fig. 3). Waves bend sharply forward over canyon. Waves are higher just outside the canyon than over the canyon, and the surf zone is narrow opposite the mouth of the canyon. (Photograph by Spence Air Photos, Los Angeles.)

PLATE III

Refraction of waves over the coral reef at Guam. Wave crests move ahead over the channels and lag behind over the shoals. Wave heights are low over channels and large over shoals. Compare with schematic drawings in Figs. 3 and 4. (Official photograph, United States Navy.)

PLATE IV

A, Refraction of waves around Point Loma, San Diego, California. Solid orthogonal shows main refraction around the point; dashed orthogonal designates secondary refraction around a shoal directly off the end of Point Loma. Notice variation in width of surf zone. (Official photograph, United States Navy.)

B, Waves turn through 180° around the hook of Cape Cod but, in doing so, lose most of their height because of the very large divergence. Notice variation in width of surf zone. (Official photograph, United States Navy.)

PLATE V

Waves bend toward the famous Waikiki Beach on Oahu, T.H. (Official photograph, United States Navy.)

PLATE VI

Photograph of a three-dimensional model of the bottom topography off La Jolla, California. Two submarine canyons, La Jolla Canyon and its steep-walled tributary, Scripps Canyon, reach within a thousand feet from shore.

PLATE VII

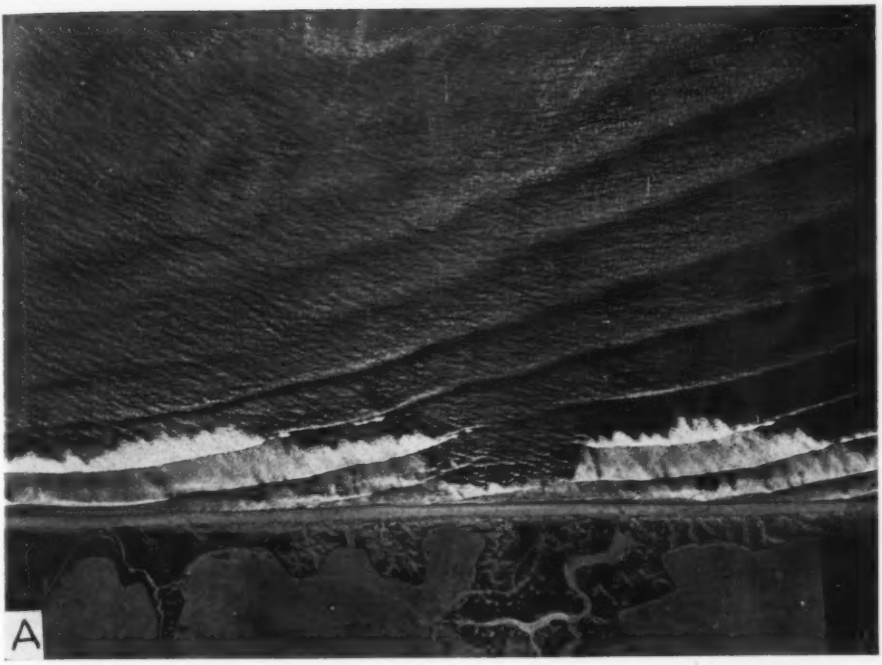
Observed versus computed orientation and spacing of wave crests. The computed positions (*inked lines*) are parallel to the positions of the crests on the photograph, except for a small discrepancy on the left side of the figure (see text).

PLATE VIII

A, Photograph of waves north of Scripps Canyon shows the presence of the crisscross pattern which appears in the refraction diagram (Fig. 17). Peaks occur where the refracted crests intersect the crests of the main wave train.

B, Refraction of waves at boat basin, Oceanside, California. Longshore currents set up by waves have widened the beach on both sides of jetties (see also Pl. II). This in turn has caused refraction of waves near jetties. The resulting refraction pattern tends to further strengthen the convergence of longshore currents upon the jetties and may lead to accelerated deposition.

PLATE I



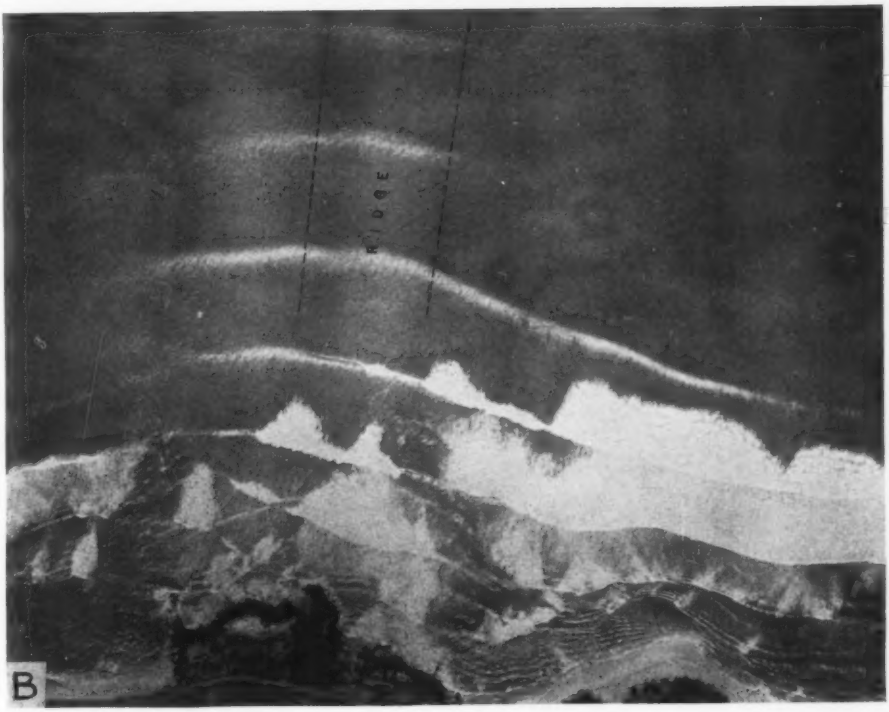


PLATE II

PLATE III

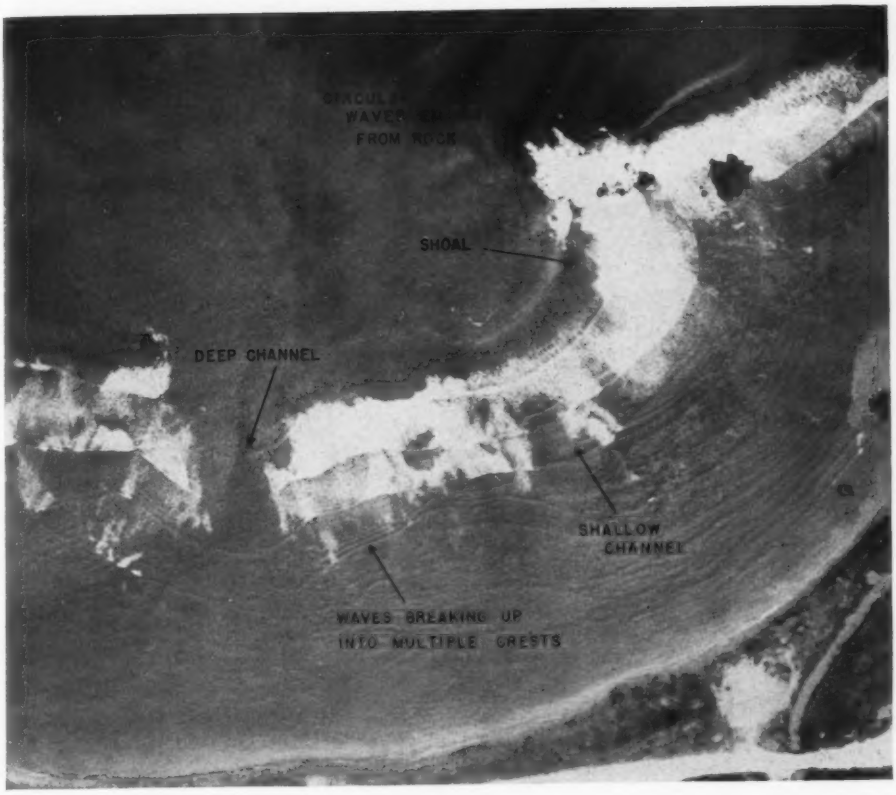

SHOAL
DEEP CHANNEL
SHALLOW CHANNEL
WAVES BREAKING UP
INTO MULTIPLE CRESTS

PLATE IV

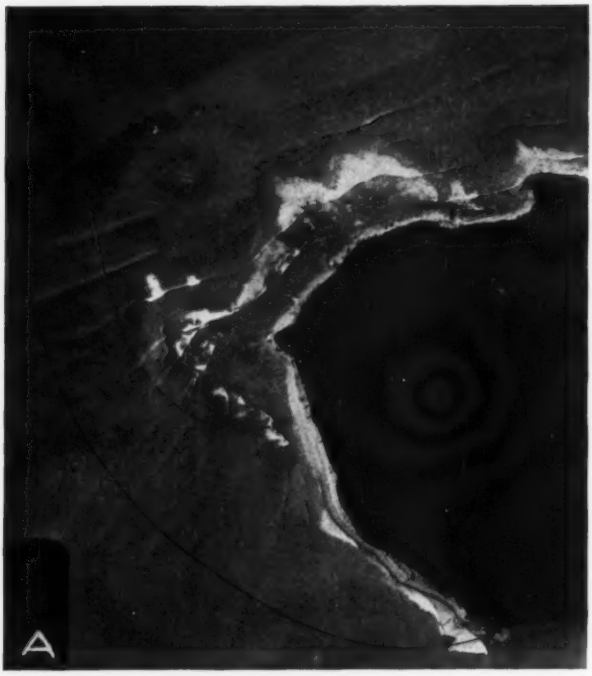


PLATE V

PLATE V

PLATE VI

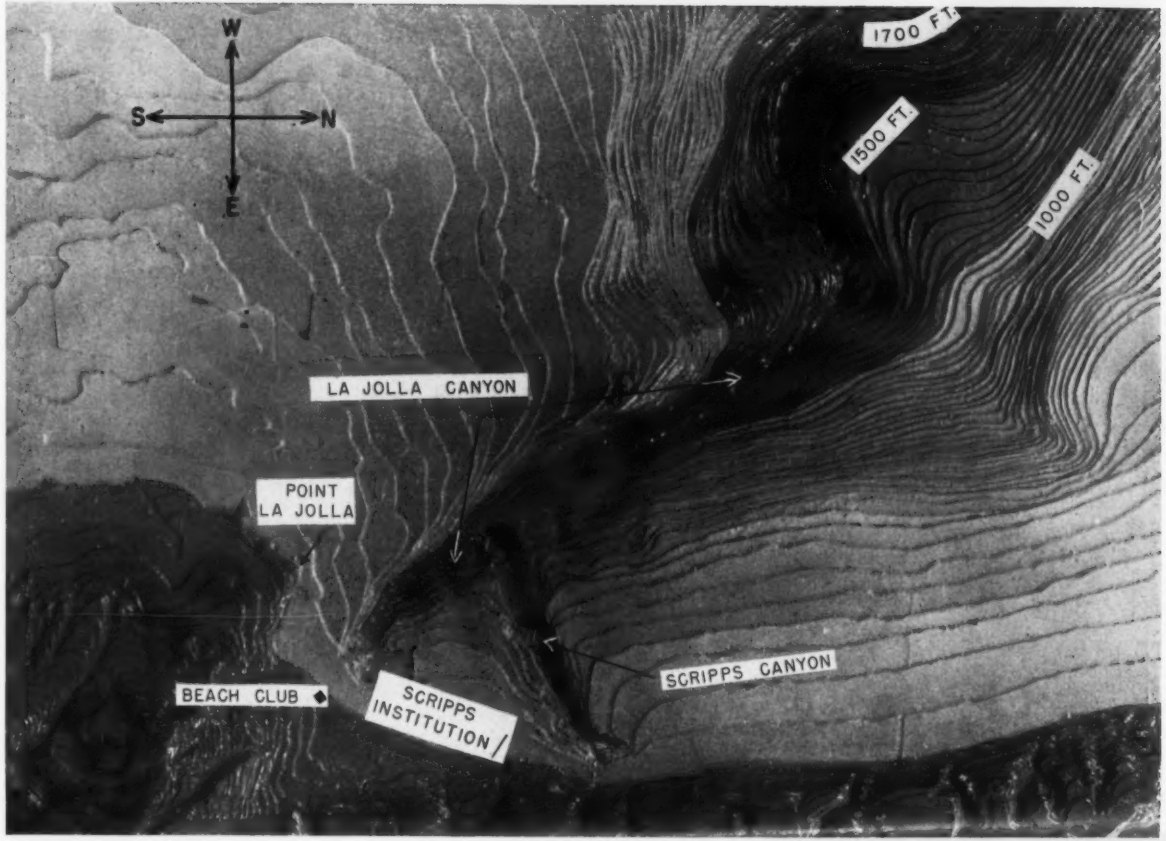
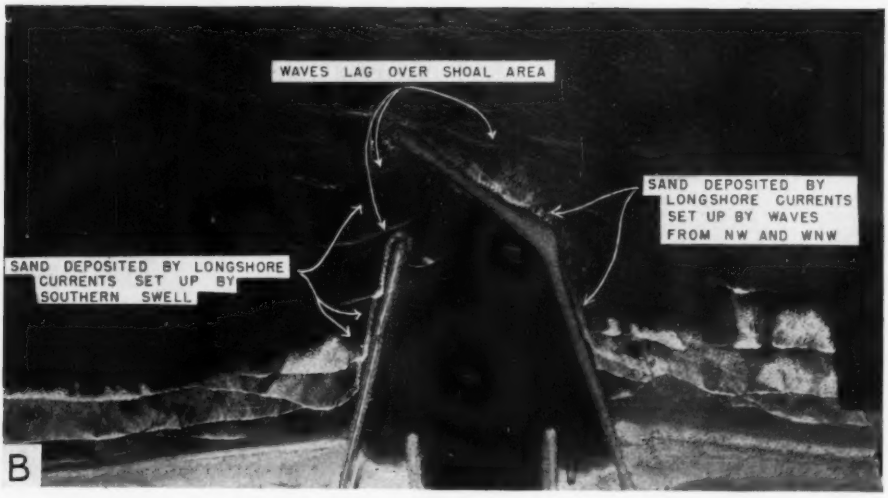


PLATE VII

6 MAY 1944 - 1005
1000 FEET

PLATE VIII

A


WAVES LAG OVER SHOAL AREA
SAND DEPOSITED BY LONGSHORE CURRENTS SET UP BY WAVES FROM NW AND WNW
SAND DEPOSITED BY LONGSHORE CURRENTS SET UP BY SOUTHERN SWELL

B

THE SYSTEM $NaAlSiO_4$-$Ca_2Al_2SiO_7$

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University of Chicago

ABSTRACT

The high-temperature phase equilibrium relations in the system $NaAlSiO_4$-$Ca_2Al_2SiO_7$ were investigated experimentally by the quenching method. The behavior of this system was found to differ from that of a true binary system in a number of important respects, and it is concluded that the system is actually quaternary. An illustration is thus provided of the extent to which equilibrium relations can be rendered complex, even in such comparatively simple melts, by the great tendency of certain minerals to form complex solid solutions.

INTRODUCTION

This investigation is a study of the high-temperature equilibrium relationships, at atmospheric pressure, of mixtures of the two silicates, sodium aluminum orthosilicate ($NaAlSiO_4$) and the calcium aluminum silicate, $Ca_2Al_2SiO_7$. These compounds are the principal molecules[1] of the natural minerals nepheline and gehlenite, respectively. Both nepheline and gehlenite are feldspathoids, important constituents of the alkaline series of igneous rocks. Nepheline is the most characteristic mineral of these rocks, while melilites, of which mineral group gehlenite is an end-member, are found in alkaline rocks rich in lime. Nepheline and melilite are found in association in some igneous rocks. Gehlenite also often occurs as a metamorphic mineral.

The compositions of all possible mixtures of the compounds $NaAlSiO_4$ and $Ca_2Al_2SiO_7$ may be expressed in terms of the four oxides, soda, lime, alumina, and silica. The system under consideration forms an internal linear join in the composition tetrahedron which has these four oxides as its apexes. The two compounds are represented by points at the ends of this join, lying on faces of the tetrahedron.

The properties of the two individual silicates were not determined in this investigation, as this information was available from the findings of other workers. Eleven different mixtures of the two components were prepared from the oxides. These were studied thermally by means of the quenching method, in which a small charge is allowed to come to equilibrium at a known temperature and then chilled rapidly by being dropped into mercury. It is then examined microscopically to determine the phases present at equilibrium. About 160 "runs" of this kind were made.

PROPERTIES OF THE CRYSTALLINE PHASES

CARNEGIEITE

Carnegieite, the high-temperature form of $NaAlSiO_4$, exists in three forms, none of which occurs in nature. It melts at a temperature of 1526° C.[2] and is isometric at high temperatures, altering metastably to a triclinic form upon cool-

[1] In spite of our present knowledge of crystals as atomic lattices and of the laws controlling the proxying of one atom for another, the concept of molecules in solid solution in crystal phases of variable composition is still a useful one, especially in studies of phase equilibriums.

[2] N. L. Bowen, "The Binary System: $Na_2Al_2Si_2O_8$ (Nephelite, Carnegieite)-$CaAl_2Si_2O_8$ (Anorthite)," *Amer. Jour. Sci.*, Vol. XXXIII (4th ser., 1912), pp. 554 ff.

ing below 690° C.[3] A second inversion occurs at a temperature of 226.5° C., accompanied by a marked change in birefringence. The indices of refraction of low-temperature carnegieite are given by Bowen[4] as $\gamma = 1.514$, $\beta = 1.514-$, $\alpha = 1.509$. Carnegieite usually lacks crystal form, occurring in small globular masses, and typically has an intricate polysynthetic twinning.

The carnegieite obtained in the present study had typical globular form, and much of it exhibited characteristic twinning. Its indices were always significantly higher than those of pure carnegietite, however, and thus indicated the presence of solid solution. This also resulted in a decrease in birefringence to the extent that separate indices could rarely be distinguished. A trend toward higher carnegieite indices was observed in mixtures successively richer in $Ca_2Al_2SiO_7$. For example, the average index for carnegieite obtained in runs near the liquidus temperatures increased from 1.516 in the 90 per cent $NaAlSiO_4$ mixture to 1.522 in the 70 per cent $NaAlSiO_4$ mixture. Likewise, the average index was higher in carnegieite which was formed at lower temperatures. Thus, in the case of the 80 per cent $NaAlSiO_4$ mixture, the index changed from 1.520 in carnegieite formed at 1399° C. to 1.523 in that formed at 1187° C. The trend toward higher indices of carnegieite in mixtures successively richer in lime appeared to reverse itself after the 30 per cent $Ca_2Al_2SiO_7$ mixture was passed. These variations in the indices of the carnegieite of this system are significant as indications of the extent to which the composition of this phase was modified by solid solution.

[3] N. L. Bowen and J. W. Greig, "The Crystalline Modifications of $NaAlSiO_4$," *Amer. Jour. Sci.*, Vol. X (5th ser., 1925), pp. 208–10.

[4] P. 564 of ftn. 2.

NEPHELINE

Pure artificial nepheline inverts to carnegieite at a temperature of 1254 ±5° C.[5] However, Bowen[6] found that solid solution of anorthite raised the inversion point of nepheline as much as 100°, while albite in solid solution has been shown[7] to raise the inversion temperature some 30°. In the present study this transformation took place over a range of temperatures extending from about 50° above to 100° below the normal inversion point.

Nepheline is hexagonal and crystallizes in melts in short prismatic crystals with basal pinacoid. Bowen[8] gives the indices as $\epsilon = 1.533$ and $\omega = 1.537$. He found that solid solution of anorthite raised the value of ϵ to as high as 1.539, ω remaining constant. Solid solution of albite in nepheline has been found[9] to lower the indices of the latter somewhat. The nepheline obtained in the present study had unusually high indices, which increased from an average value of 1.540 in runs made with the 90 per cent $NaAlSiO_4$ mixture to as high as 1.552 in the 65 per cent $NaAlSiO_4$ mixture. The birefringence usually was very low, and this made it impossible to determine optic sign except in a few cases, in which it was negative. Two distinct indices could not be measured, and the sign of elongation of the crystals was only rarely ascertainable.

[5] J. W. Greig and Tom F. W. Barth, "The System $Na_2O \cdot Al_2O_3 \cdot 2SiO_2$ (Nephelite, Carnegieite)-$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$ (Albite)," *Amer. Jour. Sci.*, Vol. XXXV-A (5th ser., 1938), p. 108.

[6] P. 571 of ftn. 2.

[7] P. 109 of ftn. 5.

[8] P. 566 of ftn. 2.

[9] W. R. Foster, "The System $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$," *Jour. Geol.*, Vol. L (1942), p. 157.

GEHLENITE

Artificial gehlenite melts congruently at a temperature of 1590° C.[10] It is tetragonal, forming short prismatic or tabular crystals with distinct basal cleavage. Its indices of refraction are 1.669(ω) and 1.658(ϵ). The melilite crystals encountered in this investigation usually had the typical crystal habit, but sometimes they assumed shapeless rounded forms, clustered together and often very minute. They differed considerably from pure gehlenite in indices of refraction. Although the indices could be determined with accuracy in only a relatively few runs, sufficient data were obtained to show a progressive decrease in indices with increase in $NaAlSiO_4$ content of the mixture. Thus, in runs made with the 30 per cent $NaAlSiO_4$ mixture the melilite indices were 1.666 ($\pm$.002) and 1.658, while in a run made with the 40 per cent $NaAlSiO_4$ mixture the indices were found to be 1.662 and 1.655. In the 60 per cent $NaAlSiO_4$ mixture, the melilite index ω reached a value as low as 1.651. In mixtures richer in $NaAlSiO_4$ than 60 per cent, the indices were somewhat higher, indicating that the trend toward lower indices is reversed at about this composition. Considering a single mixture, the indices were somewhat lower in melilite formed at lower termperatures. Thus, in runs made with the 40 per cent nepheline mixture, the indices of melilite formed at 1408° C. were 1.662 and 1.655, while those of melilite formed at 1247° C. were 1.656 and 1.650. These differences in optical properties give some indication of the extent of the variations in composition of the "gehlenites" of this system.

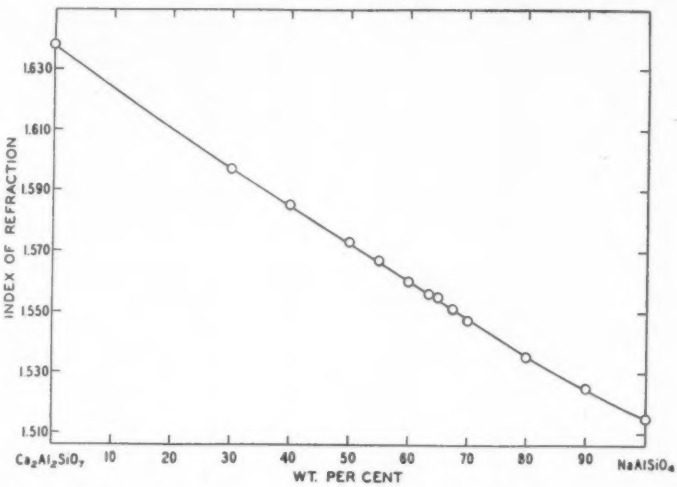

FIG. 1.—Indices of refraction for the glasses of the system $NaAlSiO_4$-$Ca_2Al_2SiO_7$

THE THERMAL DATA

In the thermal investigation eleven mixtures of different composition were prepared and studied. The refractive indices of the glasses of these mixtures are given in the graph of Figure 1. Of the 160 runs which were made, less than

[10] E. F. Osborn and J. F. Schairer, "The Ternary System, Pseudo-wollastonite-Akermanite-Gahlenite," *Amer. Jour. Sci.*, Vol. CCXXXIX (1941), p. 719.

TABLE 1

THERMAL DATA FOR THE SYSTEM $NaAlSiO_4$-$Ca_2Al_2SiO_7$

Weight Per Cent		Initial Condition	Time	Temp. (° C.)	Final Condition
$NaAlSiO_4$	$Ca_2Al_2SiO_7$				
30	70	glass	60 min.	1469	MEL and glass
		glass	35 min.	1473	All glass
40	60	glass	45 min.	1415	MEL and glass
		glass	40 min.	1420	Rare MEL and glass
		glass	60 min.	1424	All glass
50	50	glass	2 hr.	1230	MEL, rare CG, and glass
		devitr.	2 hr.	1281	MEL, rare CG, and glass
		devitr.	2 hr.	1285	MEL and glass
		glass	40 min.	1356	Rare MEL and glass
		glass	40 min.	1360	All glass
55	45	glass	2¼ hr.	1260	MEL, CG, rare NE, and glass
		devitr.	2 hr.	1264	MEL, CG, and glass
		devitr.	2 hr.	1281	MEL, CG, and glass
		devitr.	2¼ hr.	1285	MEL and glass
60	40	devitr.	2 hr.	1281	MEL, CG, NE, and glass
		devitr.	2¼ hr.	1285	MEL and glass
		glass	90 min.	1300	MEL and glass
		glass	45 min.	1304	All glass
63.5	36.5	devitr.	2 hr.	1218	MEL, NE, rare CG, and glass
		devitr.	2½ hr.	1281	MEL, NE, rare CG, and glass
		devitr.	2¼ hr.	1285	MEL, NE, and glass
		devitr.	2 hr.	1289	Very rare MEL and glass
65	35	devitr.	2 hr.	1218	MEL, NE, rare CG, and glass
		devitr.	2 hr.	1277	NE, MEL, rare CG, and glass
		devitr.	2½ hr.	1281	NE, MEL, and glass
		devitr.	2¼ hr.	1285	NE and glass
		glass	1 hr.	1290	Rare NE and glass
67.5	32.5	devitr.	2 hr.	1257	MEL, NE, rare CG, and glass
		devitr.	2 hr.	1274	CG, NE, MEL, and glass
		devitr.	2½ hr.	1278	CG, NE, and glass
		devitr.	2 hr.	1290	CG, NE, and glass
		devitr.	2¼ hr.	1294	Rare CG and glass
		glass	1½ hr.	1298	All glass
70	30	devitr.	2 hr.	1195	NE, MEL, and glass
		devitr.	2½ hr.	1199	NE, MEL, rare CG, and glass
		devitr.	2 hr.	1276	NE, CG, rare MEL, and glass
		devitr.	3 hr.	1280	CG, NE, and glass
		devitr.	1½ hr.	1296	CG, NE, and glass
		devitr.	2 hr.	1300	CG and glass
		glass	75 min.	1321	Rare CG and glass
		glass	40 min.	1325	All glass
80	20	devitr.	2 hr.	1154	NE, MEL, and glass
		devitr.	2 hr.	1171	NE, MEL, rare CG, and glass
		devitr.	2 hr.	1268	CG, NE, rare MEL, and glass
		devitr.	2 hr.	1272	CG, NE, and glass
		devitr.	3½ hr.	1296	CG, NE, and glass
		devitr.	2 hr.	1298	CG and glass
		glass	50 min.	1399	Rare CG and glass
		glass	40 min.	1404	All glass
90	10	devitr.	2 hr.	1103	NE, MEL, and glass
		devitr.	2 hr.	1154	NE, MEL, rare CG, and glass
		devitr.	3 hr.	1229	NE, CG, very rare MEL, and glass
		glass	2 hr.	1231	NE, CG, and glass
		devitr.	2 hr.	1274	CG, rare NE, and glass
		devitr.	2½ hr.	1285	CG and glass
		glass	60 min.	1465	Rare CG and glass
		glass	35 min.	1469	All glass

half were sufficient to fix the temperatures of the various transformations. The results of the critical runs are given in Table 1 on page 30. The equilibrium diagram for the system appears as Figure 2.

NONBINARY NATURE OF THE SYSTEM

Even a casual inspection of the equilibrium diagram will suffice to show that this is not a true binary system. As pointed out above, the variation of optical properties indicates that each of the three crystalline phases occurring in the system is actually a solid solution. The equilibrium diagram shows clearly that these solid solutions are not composed of the two binary components alone, but that other substances, not representable in terms of $NaAlSiO_4$ and $Ca_2Al_2SiO_7$, are also present. Perhaps the best evidence for this is the fact that the system lacks a binary eutectic. Nor are any simple solidus curves present, as would be the case were the solid solutions composed of the two components alone. In fact, liquid persists down to the lowest temperatures of observation throughout the system. During crystallization, the second solid phase does not make its appearance at any fixed temperature (eutectic) but begins to crystallize at a different temperature in each mixture. The inversion relations of nepheline and carnegieite likewise attest to the nonbinary nature of the system. Inversion takes place over a wide temperature range in mixtures on both sides of the pseudoeutectic composition. In compositions adjacent to the latter, nepheline is in equilibrium with liquid at higher temperatures than is carnegieite!

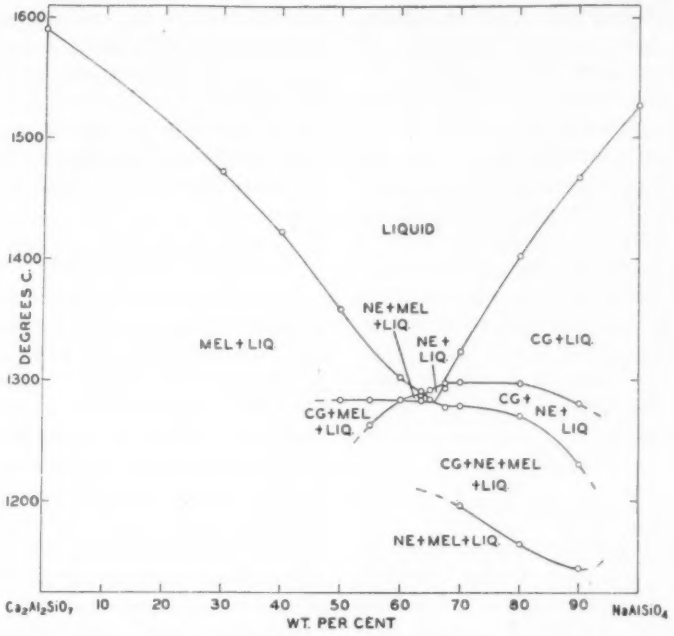

FIG. 2.—Equilibrium diagram for the system $NaAlSiO_4$-$Ca_2Al_2SiO_7$

From a consideration of the phase rule, which, as applied to a condensed system, is $P + F = C + 1$, it is clear that no more than three phases can occur in equilibrium in a binary system, and as many as three only at a fixed temperature. In one field of the equilibrium diagram for the present system four phases coexist, and in several other fields three phases occur in equilibrium. As the system is therefore not binary, the substances entering into the carnegieite, nepheline, and melilite solid solutions cannot be expressed in terms of two components. The components of the system must be considered four—the four constituent oxides present in all compositions. As many as five phases could coexist in equilibrium at an invariant point in such a system. The liquidus curves of the diagram do not then represent univariant equilibriums, but are trivariant, and the pseudoeutectic is actually divariant. The compositions of the phases lie outside the plane of the diagram and hence are not determinable for specific temperatures and compositions from this diagram.

THE LIQUIDUS RELATIONS

The melting-point of pure $Ca_2Al_2SiO_7$ is 1590° C., and that of pure $NaAlSiO_4$ is 1526° C. From these points the liquidus curves slope downward toward each other in the usual way, forming a junction at a temperature of about 1287° C. and a composition of 64 per cent $NaAlSiO_4$. As pointed out above, this is not a true eutectic point. The carnegieite liquidus has a sharp break in slope at its junction with the upper boundary of the carnegieite-nepheline inversion range—the usual effect of inversion. This junction occurs at about 1297° C. and a composition of 67 per cent $NaAlSiO_4$. Each point on these curves represents the temperature at which the first crystals appear as a charge of that composition is cooled, and the temperature where melting is completed as such a charge is heated up. The curves do not, as in a true binary system, give the compositions of the liquids in equilibrium with the separating crystals at the various temperatures. Instead, the composition of each liquid follows a path which is outside the plane of the diagram and is different for each mixture. This is because the compositions of the mix-crystals separating out do not lie in the plane of the diagram. As these crystals form, the liquid in equilibrium with them becomes progressively impoverished in the substances going to make up the crystals, and its composition necessarily leaves the plane of the diagram.

THE SECONDARY-PHASE BOUNDARIES

From the pseudoeutectic point, the secondary-phase boundaries slope downward on both sides, behaving quite unpredictably. Any point on these curves gives the temperature at which the second phase[11] makes its appearance during the cooling of a melt of the indicated composition. Liquid persists below these boundaries, although it slowly diminishes in amount as the temperature is lowered. The curve on the nepheline side of the diagram is quite gentle in slope as it proceeds away from the pseudoeutectic point, but curves rather sharply at about 80 per cent $NaAlSiO_4$, and dips steeply from that point on. The secondary-phase boundary on the gehlenite side of the diagram is nearly horizontal as far from the pseudoeutectic point as it was determined. For a short distance near that point this curve marks the upper limit of nepheline as the secondary phase.

[11] On the nepheline side of the diagram, it is actually the *third* solid phase which begins to form at this boundary, as the carnegieite-to-nepheline inversion has not been completed, and both forms of $NaAlSiO_4$ are present.

From approximately the 40 per cent $Ca_2Al_2SiO_7$ composition toward mixtures richer in that component, it lies above a field in which carnegieite is the secondary phase.

THE NEPHELINE-CARNEGIEITE INVERSION

The inversion relations between carnegieite and nepheline are quite unusual. The inversion takes place over a large range of temperatures. The upper boundary of the inversion range gives the temperature at which the first nepheline appears on cooling a melt and the last traces of nepheline disappear on heating it. Likewise, the lower boundary marks the completion of the carnegieite-to-nepheline inversion and the beginning of the opposite transformation. The upper limit of the inversion range on the $NaAlSiO_4$ side of the diagram lies at approximately 1297° C. from its junction with the liquidus to a composition somewhat richer in $NaAlSiO_4$ than 80 per cent, where it falls rather rapidly toward the normal inversion point at 1254° C. The lower limit of the carnegieite-nepheline transformation was found to be, at the 90 per cent $NaAlSiO_4$ composition, somewhat lower than 1150° C., or 100° below the normal inversion temperature. Between this composition and that of pure $NaAlSiO_4$ this boundary must slope upward toward the temperature 1254° C. In the other direction this curve also slopes upward, probably continuing to rise over into the melilite side of the diagram.

Strangely enough, nepheline is stable at higher temperatures than carnegieite for a small range of compositions close to the pseudoeutectic point. It is difficult to find an explanation for this behavior solely on the basis of the results of the present study, but it is hoped that studies of adjoining mixtures will shed light on the problem. From approximately the 40 per cent $Ca_2Al_2SiO_7$ composition toward compositions richer in that component, carnegieite is again stable at higher temperatures than is nepheline. The upper limit of inversion falls rapidly in this direction, at least where it could be definitely determined. It was useless to attempt to fix the various boundaries farther toward the $Ca_2Al_2SiO_7$ side of the diagram than they are shown, as the preponderance of melilite in the charges made it impossible to determine the exact nature of the other phases present.

THE CRYSTALLIZATION OF A TYPICAL MIXTURE

Since the exact composition of the phases in equilibrium at any point in the diagram for this system is not known, the course of crystallization for a given mixture can be described only in a general way. Thus, in the case of a melt of composition 70 per cent $NaAlSiO_4$, 30 per cent $Ca_2Al_2SiO_7$, the first crystals begin to form at a temperature of 1323° C. These are carnegieite mix-crystals. They continue to separate out until the melt has cooled down to 1298° C., causing the liquid to become continually poorer in $NaAlSiO_4$ and in the material in solid solution with it. The carnegieite solid solutions presumably become more concentrated as the temperature falls. At the temperature indicated, the carnegieite begins to invert to nepheline. As the substance in solid solution in this phase is probably different from that entering into the carnegieite solid solutions, the latter is then slowly returned to the liquid solution while the former substance is progressively subtracted from it. Melilite begins to crystallize at 1278° C. and continues to do so in the presence of carnegieite, nepheline mix-crystals, and liquid until, at 1197° C., the inversion to nepheline is complete and the last car-

negieite disappears. At some lower temperature the last of the liquid will be used up.

THE SUBSTANCES IN SOLID SOLUTION

In the foregoing, frequent mention has been made of the fact that the crystalline phases of this system are solid solutions. The nature of the substances in solid solution is, unfortunately, not decided by the results of this study. However, in each case certain facts are known which suggest a choice among the several possibilities.

Nepheline.—In the case of nepheline, several substances are known to enter into solid solution with it in considerable amount. Of the molecules entering into the composition of natural nephelines, $KAlSiO_4$ is known to form a complete solid-solution series with nepheline,[12] while albite[13] and anorthite[14] are each taken into solid solution up to 35 per cent. No potash compound is to be considered a possibility in the present case, as the system contains no potash. Anorthite is the most likely of the other two possibilities, because it is known to change the refractive indices of nepheline considerably when in solid solution with it.

If anorthite is indeed the substance present in the nepheline solid solutions, certain aspects of its behavior are not quite clear. Bowen[15] found that nepheline solid solution with anorthite underwent a change in optic sign from negative to positive as the amount of the latter substance increased. The value of the index ω remained constant, while that of ϵ increased from 1.533 to 1.539. In the present study, a more marked rise in indices occurred, a value as high as 1.552 being reached. The birefringence decreased almost to zero, but it could not be determined whether a change of optical sign took place. Bowen[16] found that solid solution of anorthite in nepheline raised the temperature of the inversion to carnegieite as much as 100°, while in the present study the upper boundary of the inversion range is at most only about 50° above the normal inversion. In this case, however, solid solution in carnegieite is also considerable, and although the substance in solid solution is, as the general relations show, not anorthite, this may affect the extent to which the inversion is raised. Anorthite may be thought of as produced by an interaction between gehlenite and nepheline as expressed by the equation $Ca_2Al_2SiO_7 + 2NaAlSiO_4 \rightleftharpoons CaAl_2Si_2O_8 + Na_2Al_2O_4 + CaSiO_3$.

Carnegieite.—The carnegieite solid solutions present a similar problem. Clearly, in this case solid solution modifies the composition of carnegieite very considerably, as indicated by marked raising of the indices of refraction and by the lowering of the inversion boundary. Inversion lowering is a very unusual phenomenon in silicate systems. This is because the high-temperature forms of enantiotropic minerals usually form solid solutions much less readily than do the low-temperature modifications. Thus, the extent of solid solution of anorthite in carnegieite is only 5 per cent, while it is 35 per cent in nepheline.[17] However, two substances are known which form more concentrated solid solutions in carnegieite than in nepheline. The artificial mineral sodium metasilicate (Na_2SiO_3) was found by C. E. Tilley[18] to enter into carnegieite solid solutions up to 24 per cent

[12] N. L. Bowen, "The Sodium-Potassium Nephelites," *Amer. Jour. Sci.*, Vol. XLIII (4th ser., 1917), pp. 115–32.

[13] P. 106 of ftn. 5.

[14] P. 563 of ftn. 2.

[15] P. 566 of ftn. 2.

[16] P. 571 of ftn. 2.

[17] P. 563 of ftn. 2.

[18] The Ternary System, Na_2SiO_3-$Na_2Si_2O_5$-$NaAlSiO_4$, *Min. u. petrog. Mitt.*, Vol. XLIII (1933), p. 414.

but not at all into nepheline. The solid solution in carnegieite caused an increase in the birefringence of that phase by increasing the value of the index γ to 1.518. It also resulted in a wide inversion interval, which extended from the normal inversion down to 1163° C. In the present case, solid solution raises the indices of carnegieite much more noticeably and results in a marked decrease in birefringence. The inversion lowering is slightly greater than in the case cited above.

Sodium aluminate ($Na_2Al_2O_4$) has also been found to enter in considerable amounts into solid solution with carnegieite,[19] although the extent to which this can occur is not known as yet. Data regarding the optical and other properties of these solid solutions are also not yet available. Of the two substances considdered, sodium aluminate is perhaps the more likely constituent of the carnegieite solid solutions under consideration. As already noted, the trend of these solid solutions is to increase in concentration with increase in the $Ca_2Al_2SiO_7$ content of the mixture. As no suitable lime-bearing compound is known, the substance sought may be one whose formation is favored by the decrease in silica rather than by the increase in lime in this direction. Sodium aluminate is just such a compound. It may be formed in these melts by a reaction between nepheline and gehlenite such as the one cited above in which gehlenite and nepheline react to give $CaAl_2Si_2O_8$, $Na_2Al_2O_4$, and $CaSiO_3$.

It is hoped that future work will provide a basis for a more definite idea of the composition of these solid solutions.

Gehlenite.—In the case of the gehlenite solid solutions there is also little indication of what the substance modifying the composition actually is. In nature, gehlenite shows a strong tendency to form complex solid solutions, so that the compositions of the natural melilites require at least four hypothetical molecules for their expression by any one of the several theories which have been advanced to explain them. Assuming that only one substance besides gehlenite enters into the composition of these artificial melilites, and reasoning from the evidence of the optical properties, as was done in the case of carnegieite and nepheline, it may be considered probable that the substance in question is a soda compound. A compound analogous to gehlenite but containing some soda is $CaNaAlSi_2O_7$, one of the hypothetical melilite molecules suggested by Winchell.[20] This differs from gehlenite only in the substitution of Na for Ca, and Si for Al, replacements consistent with present knowledge of atomic volumes. This compound may be thought of as formed by a reaction between nepheline and wollastonite, as $NaAlSiO_4 + CaSiO_3 \rightleftarrows CaNaAlSi_2O_7$. $CaSiO_3$ is one of the products of the reaction between nepheline and gehlenite cited above, by which $CaAl_2Si_2O_8$ (anorthite) and $Na_2Al_2O_4$ (sodium aluminate) are also formed. These reactions, while purely hypothetical, do serve in some measure to suggest in what ways the compositions of the liquids may change as the mix-crystals separate out.

PETROLOGIC SIGNIFICANCE

THE SODA-LIME-ALUMINA-SILICA SYSTEM

The present investigation deals with but a small part of a much larger system—the quaternary system soda-lime-alumina-silica. Knowledge of the equilibrium relations in the parent-system is of great importance in the understanding of petrologic problems. This is evident

[19] Unpublished work of J. F. Schairer and N. L. Bowen.

[20] A. N. Winchell, "The Composition of Melilite," *Amer. Jour. Sci.*, Vol. VIII (5th ser., 1924), pp. 375–87.

from a consideration of the quantitative importance of these oxides in the compositions of igneous rocks. The four together constitute 83 per cent, by weight, of the average oxide composition of igneous rocks.[21] The petrologic significance of the system may be further illustrated by listing those minerals which consist of these four oxides alone. Among these are the plagioclase feldspars, quartz, nepheline, wollastonite, gehlenite, grossularite garnet, larnite, sillimanite, corundum, mullite, and jadeite. Mention may be made of the fact that the system of four oxides has importance also in a number of technological applications. Knowledge of equilibrium relationships in this system is of fundamental importance in glass technology, the manufacture of refractories, and Portland cement manufacture.

THE SYSTEM $NaAlSiO_4$-$Ca_2Al_2SiO_7$

Comparison with natural magmas.—The synthetic melts of this system do not coincide in composition with any natural magmas. Perhaps the closest approach is found in the magmas which formed certain feldspar-free rocks of the alkaline clan, such as the urtites and ijolites, nepheline- and melilite-basalts, and the turjaites and melilite-nephelinites. Of these, the latter two types, while less common, contain prominent amounts of both melilite and nepheline, while urtites have the highest proportion of nepheline—over 70 per cent. They all contain considerable amounts of alkaline pyroxenes and a variety of accessory minerals. Also, the melilites present all contain magnesia, and thus differ from those of the present system.

The significance of the solid solutions.—The results of this investigation serve to demonstrate once again the great tendency of both nepheline and gehlenite to form solid solutions, which makes it very unlikely that any mineral will ever be found in nature having the composition of either pure compound. The fact that pure nepheline cannot exist in the presence of a lime-bearing compound has been corroborated by the experiments of several investigators. The present study shows that pure gehlenite does not form if even a small proportion of a soda-bearing compound is present. In both cases, of course, this is just what would be expected from the complexity of the compositions of the natural minerals. However, the present system, with its simplicity of composition, might be expected to yield solid phases of simple composition where more complex melts would not. If the substance in solid solution with nepheline is indeed anorthite (or a plagioclase close to anorthite in composition), another illustration is provided of the great tendency of feldspar molecules to form even in melts of such low silica content. It suggests that plagioclase may well be present, in solid solution with nepheline, even in feldspar-free rocks such as the urtites and ijolites.

Geologic thermometry.—The value of the nepheline-carnegieite inversion as a "geologic thermometer" has been discussed by many earlier investigators. This study sheds some light on the question by furnishing an even lower value for the minimum temperature at which carnegieite can be stable. In this system, carnegieite was obtained in equilibrium at temperatures somewhat below 1150° C., or 100° lower than the inversion for the pure substance. The temperature range of the inversion was as great as 150°. It seems probable that a similar inversion interval could be expected in many natural nephelines, and, were they

[21] F. W. Clarke and H. S. Washington, "The Composition of the Earth's Crust," *U.S. Geol. Surv. Prof. Paper 127* (1924), p. 16.

crystallized from magmas at temperatures above 1150° C., some carnegieite might have formed. Since none has been found in nature, it is virtually certain that the magmas which formed the nepheline-rich rocks crystallized at temperatures lower than that.

In considerations of the use of inversions as geologic thermometers, the effects of pressure should be taken into account. In the present investigation, as is customary in such studies, experiments were carried out at atmospheric pressure. High pressures would significantly shift the nepheline-carnegieite inversion temperatures, because the densities of the two phases differ considerably. The tendency would be to raise the temperature of inversion, as nepheline is the more dense.

In most of the systems in which nepheline and carnegieite have been studied, nepheline will crystallize directly without the formation of any carnegieite in melts in which there is less than a certain concentration of $NaAlSiO_4$. That is, the compositions of the melts lie outside the field of carnegieite. In systems in which the nepheline takes large amounts of another component into solid solution, certain melts crystallize entirely to nepheline mix-crystals without the formation of any carnegieite. Certain natural nephelines are known which also have the property of melting and crystallizing directly.[22] The above facts lead to the conclusion that only in rocks very rich in $NaAlSiO_4$ could carnegieite be expected to form. However, the present study furnishes a case in which carnegieite is a stable phase on both sides of the "eutectic." It is formed in all melts containing more than 50 per cent $NaAlSiO_4$, and probably also in some poorer in that component. This suggests the possibility that some nepheline-rich magmas, if also rich in lime, might have similar wide "fields" of carnegieite, embracing compositions other than those especially high in $NaAlSiO_4$.

Unusual nature of the system.—Perhaps the chief significance of the system $NaAlSiO_4$-$Ca_2Al_2SiO_7$ lies in the illustration which it affords of the extent to which complexities can appear in a system which might be expected to be binary. Many investigated systems consisting of mixtures of two substances behave in true binary fashion, i.e., the compositions of all liquid and solid solutions can be represented by points lying along the binary join. In this system only three solid phases are present, two of them enantiotropic forms of the same mineral, but the composition of each diverges from the binary join in a different direction. As the composition of the phases can be represented only in three dimensions, the binary diagram gives little information about them. It does show some unusual relations between the phases, however. Already discussed are the indeterminate low temperature of complete crystallization, the wide field of stability of carnegieite, and the anomalous reversal of the normal relations between carnegieite and nepheline for certain compositions. The puzzling aspects of this system may be made clear as the result of work on adjoining compositions.

ACKNOWLEDGMENTS.—The writer is indebted to the faculty of the Department of Geology of the University of Chicago for the laboratory facilities which made this project possible. In particular he wishes to thank Dr. Norman L. Bowen, who has given much in the way of encouragement and guidance during the course of the study. He is also indebted to Mr. Julian R. Goldsmith for one of the mixtures used and for certain data on it.

[22] H. S. Washington and F. E. Wright, "A Feldspar from Linosa and the Existence of Soda-Anorthite (Carnegieite)," *Amer. Jour. Sci.*, Vol. XXIX (4th ser., 1910), p. 69.

AN EXAMPLE OF EXFOLIATION CAUSED BY CHEMICAL WEATHERING

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ABSTRACT

Farmin has contended that the primary cause of natural exfoliation of rock surfaces is dilation due to relief of pressure. This conclusion is questioned, and evidence from a mine adit in Sonora is presented which indicates that some exfoliation results primarily from chemical disintegration without the aid of pre-existing surfaces of strain due to dilation.

POSTULATED CAUSES OF EXFOLIATION

Of the many causes postulated to explain exfoliation of rocks in nature, perhaps most attention has been given to these four: (1) insolation, (2) forest fires, (3) chemical disintegration, and (4) dilation.

Insolation has been discarded by most geologists as a possible cause of any great importance because of failure of field or laboratory evidence to support it.[1,2,3]

That exfoliation may be caused by the heat generated by forest and brush fires has been demonstrated fairly conclusively,[4,5] but this one factor cannot explain all known examples of exfoliation.

Chemical disintegration in weathering has been considered by many geologists to be an important cause of exfoliation, but Rollin Farmin[6] has attempted to relegate it to the position of a secondary cause and to explain all exfoliation, save possibly that due to fires, as resulting primarily from dilation due to removal of load on rocks.

DILATION AS A PREREQUISITE OF EXFOLIATION

Some of the examples Farmin cites lend support to his hypothesis, and there can be little question that the sheet structure observed in many domes is due to relief from load.[7] On the other hand, the onionskin structure of the pebbles he describes in the Tintic pebble dikes could be due to contact with hot fluids rather than to release of pressure; indeed, it is difficult to visualize release of pressure as the primary agent in forming this structure in a small, hard quartzite pebble. Pebbles recovered from the bottoms of deep oil wells might furnish evidence on this point.

Donald Barton[8] has attempted to disprove Farmin's thesis by showing that exfoliation of granite in Egypt is better developed where the rock is subjected to

[1] Eliot Blackwelder, "Exfoliation as a Phase of Rock Weathering," *Jour. Geol.*, Vol. XXXIII (1925), pp. 793–806.

[2] Eliot Blackwelder, "The Insolation Hypothesis of Rock Weathering," *Amer. Jour. Sci.*, Vol. XXVI (1933), pp. 97–113.

[3] David T. Griggs, "The Factor of Fatigue in Rock Exfoliation," *Jour. Geol.*, Vol. XLIV (1936), pp. 783–96.

[4] Eliot Blackwelder, "Fire as an Agent in Rock Weathering," *Jour. Geol.*, Vol. XXXV (1927), pp. 134–40.

[5] K. O. Emery, "Brush Fires and Rock Exfoliation," *Amer. Jour. Sci.*, Vol. CCXLII (1944), pp. 506–8.

[6] "Hypogene Exfoliation in Rock Masses," *Jour. Geol.*, Vol. XLV (1937), pp. 625–35.

[7] Richard H. Jahns, "Sheet Structure in Granites," *Jour. Geol.*, Vol. LI (1943), pp. 71–98.

[8] "Discussion: The Disintegration and Exfoliation of Granite in Egypt," *Jour. Geol.*, Vol. XLVI (1938), pp. 109–11.

more moisture, but this argument does not disprove the existence of a primary structure due to dilation; the effect of moisture could still be only secondary. Where no exfoliation was noted, it would be possible to argue that invisible surfaces of strain did exist, awaiting the helping hand of hydration to develop into exfoliation.[9]

If it is granted that dilation may be one cause of exfoliation (as distinct from sheeting) of boulders and small outcrops, can it be considered the only primary cause in nature, aside possibly from forest fires? Omitting from discussion spheroidal structures in mine dumps—until an example is found of an exfoliated rock mass which can be proved never to have been under great load—one must rely on the general form and structure of certain exfoliated and spheroidal surfaces. It is common to observe granite outcrops with a hemisphere or small dome in each quadrilateral formed by the intersection of two joint sets[10] or rows of small domes between parallel joints. In many such outcrops the rounded forms are obviously the result of the modification of corners and edges produced by random joint intersections. Such general considerations lead one at once to question the wide applicability of Farmin's conclusion. Nevertheless, even for such examples, the proponent of dilation could put up arguments in favor of his theory which might be difficult to disprove positively, strain though they might the theory of probability. However, a mine adit examined by the writer in December, 1945, provides more convincing evidence on this question.

[9] Rollin Farmin, "Discussion: The Disintegration and Exfoliation of Granite in Egypt," *Jour. Geol.*, Vol. XLVI (1938), pp. 892–93.

[10] James Romanes, "Geology of a Part of Costa Rica," *Quart. Jour. Geol. Soc. London*, Vol. LXVIII (1912), p. 136.

SPHEROIDAL FORMS IN A SONORA ADIT

The Hollingsworth adit, driven in 1925 at an elevation of about 6,500 feet into the western face of Realito Mountain near the summit, lies about 9 miles southeast of Tarachi, Sonora, or 228 miles due south of Animas Station on the Southern Pacific Railway in New Mexico. The adit is straight, close to horizontal, and 223 feet long. It runs south 71° east from the portal and averages about 7 feet high and 5 feet wide. The rock exposed in the adit is the predominant rock of the region for miles around and is a porphyritic and pyroclastic volcanic of andesitic composition characterized by rather weak banded structure, mostly at dips less than 30°, and abundant rounded to subangular inclusions from an inch to a foot in diameter of rock of the same medium-grain size and appearance as the enclosing rock.

The greater part of the adit shows exfoliation to a marked degree; the walls and back are smooth, rounded, and undulating, and the floor is covered to a depth of about 1 foot with the granular and scaly residue from the back and walls. The individual spheroidal knobs are from 1 foot to 3 feet in diameter, but the exfoliation has not proceeded to the point of producing forms which project more than about 8 inches out from the wall. Layers of crumbly scale, 0.02 inch to 0.10 inch thick and totaling several inches in thickness, cover much of the walls and to a less extent the back. These layers can be easily knocked off with a pick or even with the fingers, exposing very smooth, rounded, and fairly hard spheroidal bedrock underneath.

No exfoliation is found for the first 28 feet in from the mouth of the adit. From 45 feet to 65 feet the rounding is most highly developed, but with increased distance from the portal the individual

scales are found to be thicker, and beyond 65 feet many spalls 1 inch to 2 inches thick are present. Beyond 105 feet rounding is not well developed, and instead of scale there are spalls 0.25 inch to 5 inches thick. At 160 feet from the portal there is a strong seep of water from the back, and from this point to the face the walls and back are wet. No exfoliation and no rubble on the floor are found from 160 feet to 213 feet, and in this section the adit cuts rock showing considerably more hydrothermal alteration than the rest of the adit. From 213 feet to 223 feet exfoliation is again encountered.

In the length of adit where spheroidal weathering is best developed, from 45 feet to 65 feet, the rock is similar in every other respect to that of the rest of the adit up to 160 feet. The spheroids cut indiscriminately across included fragments and fracture planes, and the amount of alteration, which in all parts of the adit is distributed erratically, appears to have had no effect on the development of the rounded forms. Where the spheroidal weathering is less well developed, fractures and narrow mineralized seams affect the shape of the spheroids.

The western slopes of Realito Mountain, under which this adit was driven, experience less marked diurnal changes in temperature than the plateau country of Sonora at a similar elevation. In winter the range is from about 35° to about 65°; in summer it is about 60° to about 85°, with occasional extremes above and below these figures. The annual precipitation is 15 inches or less. As this adit has only one outside connection and enters a steep hill, most of it remains at a nearly constant temperature the year round, the extreme of variation probably being not more than one or two degrees Fahrenheit. The air temperature in most of the adit is probably about 70° F.; the relative humidity is probably between 70 and 90 per cent. After working several hours one night in December near the face of the adit, the writer walked out of the adit at 3:00 A.M. He first noticed a change in air temperature (a drop) at 28 feet from the portal, just at the limit of exfoliation going out.

THE HOLLINGSWORTH ADIT AND THE DILATION HYPOTHESIS

Insolation, of course, cannot be a factor in the exfoliation and spheroidal disintegration of these rock surfaces. Furthermore, there is no evidence that there has ever been a fire in the adit. Chemical disintegration and dilation are the only two processes which might have been operative to produce the forms seen, for there is nothing to suggest that the rounded forms have been inherited from a flow or pillow structure in the original rock; the rounded surfaces cut across included fragments and are not parallel to the banding of the rock even in the most general way.

That there has been chemical disintegration in the Hollingsworth adit is obvious. Has it followed, however, an earlier spheroidal structure caused by dilation? If the rounded surfaces in this adit were due to dilation, some of the knobs should approximate spheres or hemispheres, but they do not. Each knob is a small segment of a sphere, and immediately adjacent to it are other knobs, both smaller and larger. In other words, any knob which one may select and which one may in theory project into the rock wall as a sphere will intersect several other spheres thus projected. If, then, these curved surfaces are the reflection of an internal structure of the rock due to dilation, the dilation pattern of

the rock is unbelievably complicated, and it remains difficult to explain why some few of the partial spheres never developed into more nearly complete spheres. A simpler and more obvious explanation is that the surfaces are merely the modification of the irregular protuberances which were left after each blast on the walls and back of this adit as it was run. The influence of fractures and narrow seams on the shape of the knobs, particularly in those parts of the adit where the spheroidal weathering is less perfectly developed, supports this explanation. It is as if one were to run over the walls and back of an ordinary crosscut with sandpaper, smoothing out the bumps but not rubbing them entirely away. Would not this be the normal and expected result of the chemical action of moist air on an irregular surface of rock of the proper composition?

Farmin[11] mentions exfoliated structures of spheroidal type in a mine in Amador County, California, but I gather from his very brief description that what he observed were sections through spheroidal structures along directions the working happened to take, just as one may cut through a spheroidally exfoliated boulder in building a road, revealing concentric circles on the side of the cut. There is nothing of this description in the Hollingsworth adit. It is the conclusion of the writer, therefore, that the rounded surfaces seen in this adit in Sonora are due to the simple action of moist air on an uneven rock face.

SOME FACTORS INFLUENCING THE FORMATION OF SPHEROIDS

It might be supposed from the short time in which these surfaces have formed that the country rock in this region is particularly well adapted to the formation of spheroids, but spheroidal weathering is almost nonexistent in the many surface exposures of this same rock near by and for miles around. On the other hand, soft rocks as well as hard, and altered rocks as well as fresh, show good spheroidal forms in the adit.

There is probably, however, a limit to the differences in physical and chemical characteristics of this particular rock beyond which spheroidal weathering will not take place. The rock from 160 feet to 213 feet from the portal of the adit, which is well altered hydrothermally, does not show these forms. However, even here, this may be explained on another basis: the constant dampness of the walls and back of the adit in this section. These surfaces are probably damp the year round, for the writer visited the adit in a period when there had been no precipitation for many months. The rock in the rest of the adit is dry and is almost certainly in this condition the year round.

The conclusion seems inescapable that, given a rock which can form spheroidal surfaces upon weathering, such forms may be developed in a very few years under conditions of constant temperature merely by maintaining the proper humidity, and possibly temperature. Near the portal of the Hollingsworth adit the dry air from outside reduces the humidity of the air inside sufficiently to prevent the formation of spheroids in this particular rock. Near the face of the adit either the dampness of the surfaces or the type of rock alteration prevents the formation of the spheroids; the writer is inclined to consider the dampness to be the controlling factor, for parts of this highly altered zone contain rock that is quite hard and ap-

[11] Pp. 626–27 of ftn. 6.

parently similar to the rock elsewhere. In other words, moist air at a constant temperature appears capable of producing spheroidal weathering shapes on a dry rock exposure.

It must not be assumed, however, from this discussion that the right conditions of humidity and temperature alone can produce spheroidal disintegration in any rock. If this were the case, spheroidal forms would be extremely common in mines throughout the world, and such is far from the truth. What is needed apparently is a medium-grained to coarse rock which disintegrates into a sand. Rocks which slough off in chunks or in powder will not produce the spheroids; the chunks follow joints, the powder is not cohesive. In some granular rocks, however, given the proper conditions of disintegration, the concentric shells which tend to form are sufficiently cohesive to allow the rock to peel and to allow the alteration to progress uniformly into the rock along the most efficient geometrical front: a curved surface.

ELECTRODE POTENTIALS AND FREE-ENERGY CHANGES IN GEOLOGY

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ABSTRACT

By use of electrode potentials and free-energy changes the term "chemical affinity" may be placed on a quantitative basis. The significance and application of these two concepts to geology is briefly suggested. For example, one may explain more satisfactorily why certain elements occur most commonly in the free state, whereas others are found invariably in compounds.

INTRODUCTION

For many years it has been a common practice in geology to use the term "affinity" in reference to the mutual attraction of certain chemical elements. This term is strictly a qualitative one expressing the attraction between the element in consideration and other elements or radicals. It has been used to explain why certain elements invariably form compounds in nature whereas others occur commonly in the native state. For example: in explaining the nonoccurrence of sodium as a native element, it is said that sodium has such a great affinity for other elements that it cannot exist uncombined; on the other hand, it is concluded that platinum occurs as a native element by virtue of its low affinity for other elements and, therefore, its weak tendency to form compounds.

It is the purpose of this paper to show how the term "affinity" may be placed on a quantitative basis through the use of electrode potentials and free-energy changes. Since most geologists are unfamiliar with the details of the concepts of electrode potentials and free-energy changes, a brief, but adequate, treatment of these two concepts will be given here; and it will be pointed out how free-energy changes help to explain the chemical states in which we find the numerous chemical elements. Those interested in a more detailed treatment of these concepts are referred to the numerous publications listed at the end of this paper.

ELECTRODE POTENTIALS

If we were to construct a cell composed of a zinc electrode and a platinum electrode immersed in a solution of zinc chloride and hydrochloric acid and to connect the electrodes by an electrical conducting wire to which a voltmeter is attached in parallel, we could measure the electrical drop across the cell. As the electrons flow through the wire, the following reactions take place in the cell: (1) At the zinc electrode the metallic zinc becomes ionized, and electrons are set free. (2) At the platinum electrode ionized hydrogen is converted to hydrogen gas by the addition of electrons. These reactions may be written as follows:

(1) At the Zn electrode:

$$Zn = Zn^{++} + 2e^{-}$$

(2) At the Pt electrode:

$$2H^{+} + 2e^{-} = H_2 .$$

Adding these two electrode reactions we get the total reaction taking place in the cell.

Total cell reaction:

$$Zn + 2H^{+} = Zn^{++} + H_2 .$$

Any oxidation-reduction reaction may be split into two "couples" which indicate the manner in which the electrons are transferred. Using the example given the reaction

$$Zn + 2H^+ = Zn^{++} + H_2$$

may be written as two couples:

$$Zn = Zn^{++} + 2e^-$$

$$H_2 = 2H^+ + 2e^- .$$

Now, let us assign to the H_2(gas)–H^+(ion) couple an electrode potential (abbreviated E°) value of zero. This is merely an arbitrary assignment, and we could just as well have assigned a zero electromotive force to the Zn–Zn^{++} couple. It is conventional, however, to assign the H_2–H^+ couple an electromotive force of zero. Hence we may say:

$$H_2 = 2H^+ + e\,2^- \qquad E^0 = 0.000 \text{ volts.}$$

If we now read the voltmeter attached to the cell described, we will obtain a value of

$$E^0 = 0.7620 \text{ volts.}$$

This electromotive force of 0.7620 volts is due to a combination of the Zn–Zn^{++} couple and the H_2–H^+ couple. Since the H_2–H^+ couple was assigned an electromotive force of zero volts, then it may be considered that the total electrical drop across the cell is due to the Zn–Zn^{++} couple. This may be stated:

$$Zn = Zn^{++} + 2e^- \qquad E^0 = 0.7620 \text{ volts.}$$

In a similar manner the potentials of other elements may be measured, but in many cases indirect methods must be used. Such determinations have been made for many of the elements, and the values given are for certain standard conditions. These conditions are: a temperature of 25° C., a fugacity (thermodynamic pressure) of one atmosphere for all gases involved, and an activity (thermodynamic concentration) of one molal (one mole per 1,000 grams of water) for all dissolved substances. Table 2 gives the values of E° for many of the metals. This list has been prepared from some of the more standard publications, and it is realized that the values given may not in all cases be from the most reliable source; however, they are sufficiently accurate for the present purpose. The electrode potentials have not been determined for many elements notable among which are most of the rare earths and, of course, the newly discovered transuranic elements.

SIGNIFICANCE OF ELECTRODE POTENTIALS

It is conventional to write all couples with the electrons on the right-hand side of the equation. Thus a positive value of a potential for a couple like

$$Ca = Ca^{++} + 2e^- \qquad E^0 = 2.87 \text{ volts}$$

means that the reaction

$$Ca + 2H^+ \rightarrow Ca^{++} + H_2$$

will proceed from left to right, as written. On the other hand, a negative value of E° implies that the reaction will proceed from right to left. For example:

$$Ag = Ag^+ + e^- \qquad E^0 = -1.42 \text{ volts}$$

means that the reaction

$$Ag + H^+ \leftarrow Ag^+ + \tfrac{1}{2}H_2$$

goes from right to left, as written.

These reactions may now be stated more simply as follows:

1. A reaction with a positive electrode potential tends to proceed from left to right.
2. A reaction with a negative electrode potential tends to proceed from right to left.

FREE-ENERGY CHANGES

In order to compare quantitatively the affinities of elements we must introduce the free-energy concept. The total energy content of a body is considered to consist of bound and free energy. Bound energy may be involved in such changes as those of state, whereas the free energy alone may be capable of transformation into other forms of work. It can be proved theoretically, however, that there must be a decrease of free energy in any reaction proceeding of its own accord.

In a reaction the bound energy may either decrease (be partly converted into heat), remain unchanged, or increase. If the decrease of free energy in a reaction is greater than the increase of bound energy, the reaction is exorthermic; but if the decrease of free energy is less than the increase of bound energy, the reaction is endothermic. Therefore, it is important to know the free energy gained or lost in a reaction rather than whether the effect is exothermic or endothermic. It might be added, however, that frequently the difference between the free energy and the total energy coming into play in a reaction is not great.

In conclusion, it is to be noted that substances tend to exist in the state which has the lowest free energy. Hence, in a reaction which involves a decrease in free energy the reaction tends to go to the right. For example, in the reaction

$$Na = Na^{+} + e^{-}$$

the sodium ion has a lower free energy than the sodium atom, and so the reaction goes toward the right. Conversely, a reaction involving an increase in free energy will proceed from right to left, as this direction favors the formation of the state with the lower free energy.

The relation between electrode potentials and free-energy changes may now be stated:

$$\Delta F^{0} = -n\mathfrak{F}E^{0},$$

in which ΔF° is the change in free energy involved between the two sides of a couple, n is the number of electrons involved in the couple, $\mathfrak{F}$ is a constant having a value of 23,070 calories, and E° is the electrode potential of the couple. From this formula it is obvious that a negative electrode potential will give a positive free-energy change, both favoring a reaction from right to left; conversely, a positive electrode potential will give a negative free-energy change, favoring the reaction from left to right. This relationship is summarized in Table 1. It is to be borne in mind that electrode potentials should not be quantitatively compared, but changes in free energy must be used in making actual quantitative comparisons.

TABLE 1

REACTION DIRECTIONS

Sign of E°	Sign of ΔF°	Direction of Reaction
+	−	→
−	+	←

GEOLOGICAL APPLICATIONS

The low affinity possessed by many metals which occur in the native state and the great affinity of metals which are found in a combined state can be expressed quantitatively and understood more easily if we refer to Table 2. By

our previous reasoning we would not expect those metals exhibiting positive electrode potentials, and hence negative free-energy changes, to occur free in nature because they tend to form ions (i.e., the reactions go from left to right), causing them to enter into compound formation. It is obvious that these metals generally do not occur free. In a like manner, with all metals showing a negative electrode potential and hence a positive free-energy change, the tendency of the reaction is from right to left, which is against compound formation. This leads us to expect these substances to exist in the native state, which is generally found to be the case.

TABLE 2

ELECTRODE POTENTIALS AND FREE-ENERGY CHANGES

Couple	E° (In Volts)	ΔF° (In Calories)
$Ba = Ba^{++} + 2\epsilon^-$	2.90	−133,800
$Sr = Sr^{++} + 2\epsilon^-$	2.89	−133,300
$Ca = Ca^{++} + 2\epsilon^-$	2.87	−132,400
$Al = Al^{+++} + 3\epsilon^-$	1.67	−115,600
$Mg = Mg^{++} + 2\epsilon^-$	2.34	−108,000
$Ti = Ti^{++} + 2\epsilon^-$	1.75	− 80,750
$Li = Li^{+} + \epsilon^-$	3.02	− 69,670
$Cs = Cs^{+} + \epsilon^-$	3.02	− 69,670
$Rb = Rb^{+} + \epsilon^-$	2.99	− 68,980
$K = K^{+} + \epsilon^-$	2.92	− 67,400
$Na = Na^{+} + \epsilon^-$	2.77	− 63,590
$Cr = Cr^{+++} + 3\epsilon^-$	0.71	− 61,860
$Mn = Mn^{++} + 2\epsilon^-$	1.05	− 48,450
$Zn = Zn^{++} + 2\epsilon^-$	0.76	− 35,100
$Fe = Fe^{++} + 2\epsilon^-$	0.44	− 20,300
$Cd = Cd^{++} + 2\epsilon^-$	0.40	− 18,460
$Co = Co^{++} + 2\epsilon^-$	0.28	− 12,840
$Ni = Ni^{++} + 2\epsilon^-$	0.25	− 11,540
$Sn = Sn^{++} + 2\epsilon^-$	0.14	− 6,500
$Pb = Pb^{++} + 2\epsilon^-$	0.13	− 6,000
$Fe = Fe^{+++} + 3\epsilon^-$	0.036	− 2,530
$H_2 = 2H^{+} + 2\epsilon^-$	0.000	0
$Cu = Cu^{+} + \epsilon^-$	−0.552	12,040
$Cu = Cu^{++} + 2\epsilon^-$	−0.348	15,900
$Ag = Ag^{+} + \epsilon^-$	−0.780	18,450
$2Hg = Hg_2^{++} + 2\epsilon^-$	−0.799	36,900
$Pd = Pd^{++} + 2\epsilon^-$	−0.83	38,300
$Au = Au^{+} + \epsilon^-$	−1.68	38,700
$Hg = Hg^{++} + 2\epsilon^-$	−0.85	39,200
$Pt = Pt^{++} + 2\epsilon^-$	−1.2	55,000
$Au = Au^{+++} + 3\epsilon^-$	−1.42	98,000

Two logical conclusions may now be stated:

1. The more negative the change in free energy (calculated from $\Delta F^\circ = -n\mathfrak{F}E^\circ$) of an element, the greater the tendency toward compound formation and, theoretically, the less the probability of finding it free in nature.

2. The more positive the change in free energy (calculated from $\Delta F^\circ = -n\mathfrak{F}E^\circ$), the less the tendency toward compound formation and, theoretically, the greater the probability of finding it free in nature.

The writers do not wish to imply that the position of a metallic element in Table 2 is an infallible indication of its affinity for other elements. The elements are arranged in order of free-energy changes, which in turn are related to electrode potentials, as already explained. The conditions for which these values apply are: a temperature of 25° C., a fugacity of one atmosphere for all gases involved, and an activity of one molal for all dissolved substances. Under different conditions of temperature, confining pressure, and concentration the values of E° and ΔF° will differ; and the relative positions of certain elements may change. For purposes of comparison, however, data applicable to standard conditions seem logical and proper.

Although the table does not contain values for anions, the effects of these elements in compound formation cannot be ignored. Even though a particular cation may have a strong positive value for ΔF°, there may be an anion, with a strong negative value for ΔF°, available in nature and ready to combine with it. The writers, however, have intentionally omitted the anions from the table for the sake of simplicity. It is their intention to consider the effects of the anion as well as of the cation in compound formation in a succeeding paper.

Again, the values in Table 2 apply to

water solutions, and obviously should apply only to water-formed minerals.

At best, then, the table is actually a guide, because all reactions must be calculated or determined independently and cannot always be predicted. After all, the values for free-energy change are indicative of conditions at equilibrium; they show whether or not a given reaction may take place. They indicate neither the rate of reaction nor the length of time necessary to attain equilibrium.

In conclusion, it appears that the affinity of metallic elements may be expressed more quantitatively on the basis of free-energy changes. Table 2 indicates, therefore, why elements like gold, platinum, and palladium almost invariably occur free in rocks of the earth's crust; why silver, copper, and mercury less commonly occur free; why iron, lead, tin, nickel, cobalt, and zinc are rarely found in the native state; and why elements near the top of the list invariably form compounds. It must be emphasized, however, that there are numerous cases in which Table 2 apparently does not apply. Many of these will be considered in detail in a forthcoming paper.

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A TECTONIC INTRUSION OF SHALE IN ROCKBRIDGE COUNTY, VIRGINIA[1]

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ABSTRACT

A strange pipe-like mass of black shale and limestone in dolomite is exposed on U.S. Route 11 about 4 miles south of Lexington, Virginia. This mass is probably a tectonic intrusion caused by intense folding.

A peculiar mass of contorted black shale and gray crystalline limestone included in dolomite is exposed in a cut on U.S. Route 11 about 4 miles south of Lexington, Rockbridge County, Virginia. On the east side of the highway the mass is about 15 feet wide at the base and 7 feet wide at the top of the cut, which is about 15 feet deep (Fig. 1). Across the highway the shale-limestone mass is about 70 feet wide through the whole exposure. Shale, on the east side of the highway, is in direct contact with dolomite except at road level, where a small wedge of limestone intervenes on the north side. On the west side of the highway, however, 55 feet of crystalline limestone separates the shale from the dolomite to the north but is absent to the south (Pl. I). Continuous outcrops in a stream that flows parallel to, and about 50 feet west of, the road include no shale and no crystalline limestone in strike with the shale-limestone mass in the road cut. Furthermore, east of the highway there is no evidence of the shale-limestone mass in the bedrock. It is thus reasonably certain that the mass is a lenticular body about 100 feet long and not more than about 70 feet wide (Fig. 1).

Within the shale-limestone mass the rocks are so complexly deformed that, except along the contact of the shale and limestone, stratification cannot be traced continuously through the mass. Around the mass, however, the strata seem to be in normal sequence, though locally overturned. They include, from oldest to youngest, the Beekmantown, Mosheim(?) Holston(?), and Athens formations.[2] A disconformity with a relief of more than 100 feet occurs in places above the Beekmantown formation.[3] The Ordovician in the Lexington area consists, from the base upward, of the Chepultepec, Beekmantown, Murfreesboro, Mosheim, Lenoir, Holston, Whitesburg, Athens, Chambersburg, and Martinsburg formations.[4] No rock of typical Murfreesboro or Lenoir lithology has been positively identified in the vicinity of the shale-limestone mass south of Lexington. Limestone similar to the Mosheim occurs in small discontinuous masses along the boundary between the Holston-type limestone and Beekmantown formation, but in most places the Holston-type limestone lies directly upon the Beekmantown. Furthermore, the thickness of this

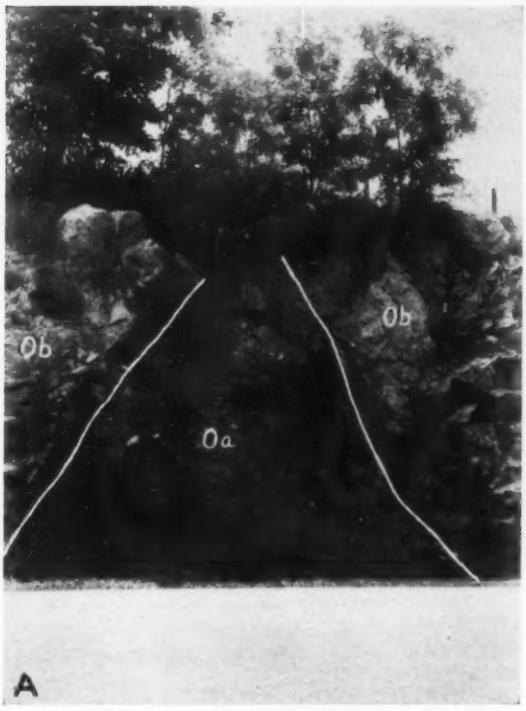
[1] Published with the permission of the state geologist of Virginia.

[2] Charles Butts, "Geology of the Appalachian Valley in Virginia," *Va. Geol. Surv. Bull. 52* (1940), Part I, pp. 102–19, 135–39, 148–54, 159–70.

[3] *Ibid.*, p. 119. See also Byron N. Cooper, "Geology and Mineral Resources of the Burkes Garden Quadrangle, Virginia," *Va. Geol. Surv. Bull. 60* (1944), pp. 31–34.

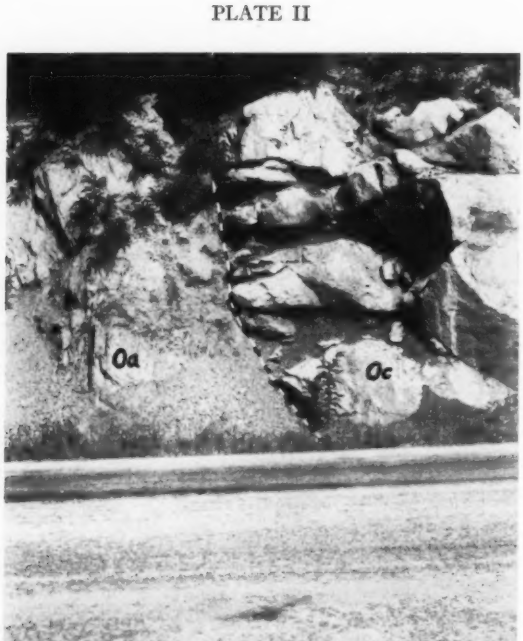
[4] Charles Butts, "Geologic Map of the Appalachian Valley of Virginia with Explanatory Text," *Va. Geol. Surv. Bull. 42* (1933), map in pocket.

PLATE I



A, Tectonic intrusion of Athens shale (*Oa*) in Beekmantown dolomite (*Ob*) on the east side of United States Route 11, about 4 miles south of Lexington, Virginia. *B*, Tectonic intrusion of Athens shale (*Oa*) and Holston limestone (*Oc*) in Beekmantown dolomite (*Ob*) on the west side of United States Route 11, about 4 miles south of Lexington, Virginia.

PLATE II



The overturned contact of the Athens shale (*Oa*) and Holston limestone (*Oc*) on United States Route 11 about 300 feet north of the tectonic intrusion.

limestone varies from a minimum of 13 feet to a maximum of more than 100 feet. Just east of the shale-limestone mass the contact of the Beekmantown and younger limestone is decidedly irregular, with pinnacles or tongues of the older formation projecting a hundred feet or more into the limestone. The character of the post-Beekmantown erosion surface clearly indicates solution or karst erosion, at least on a small scale, prior to the deposition of the overlying strata. The absence of the Murfreesboro, the discontinuity of the Mosheim-like masses, the variable thickness of the Holston-type limestone, and the tongue-like projections of the Beekmantown into younger formations are evidence of the disconformity at the top of the Beekmantown formation. The absence of the Lenoir formation, normally above the Mosheim formation, cannot be explained by this unconformity. The so-called Mosheim in the vicinity of the shale-limestone mass has been identified on the basis of lithology only. Consequently, this vaughnitic rock, in places between the Holston-type limestone and the Beekmantown, may not be Mosheim and may actually represent a unit younger than the Lenoir. If this interpretation

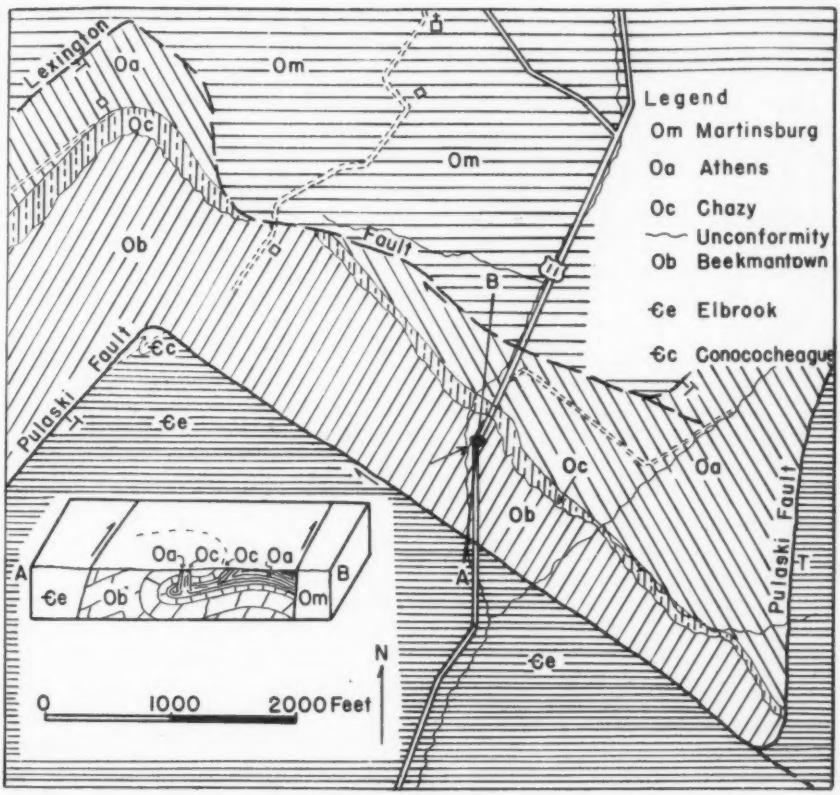


FIG. 1.—Geologic map of a small area 4 miles south of Lexington, Virginia

is correct, the unconformity above the Beekmantown may represent a hiatus that includes the Murfreesboro, Mosheim, and Lenoir formations. In other words, the Stones River group may be entirely missing at this locality.

The Holston-type limestone in the vicinity of the shale-limestone mass is stratigraphically overlain by black shale which is probably part of the Athens formation. The contact of these formations, where exposed on U.S. Route 11 about 300 feet north of the shale-limestone mass in the Beekmantown dolomite, is overturned. The black shale in the shale-limestone block included in the section of Beekmantown dolomite in the road cut is almost certainly the same formation as the shale 300 feet to the north. The limestone in the shale-limestone block is probably Holston limestone.

The relations of the small shale-limestone mass to the surrounding dolomite suggest faulting. B. N. Cooper and W. R. Brown,[5] of the Virginia Geological Survey, suggested that the shale-limestone block was dropped along gravity faults in an anticline. The major structure in which the block is contained is an anticline with the Elbrook formation thrust faulted upon the south limb, Beekmantown dolomite in the core, and the Holston and Athens formations on the north limb. The north limb of this anticline is overturned 300 feet north of the shale-limestone block (Pl. II). If the shale-limestone block were dropped along peripheral gravity faults, it is difficult to account for the relations of the limestone and shale in the block without postulating several faults. Furthermore, the severe cataclastic deformation of the rocks in the block indicates strong squeezing which seems incompatible with a structure produced by tension and gravity. If the block moved downward along gravity faults, the mass would probably have undergone little compression.

The attitude of the strata, the local stratigraphy, and the structure within the block suggest that the block moved into the Beekmantown dolomite from below. Just 300 feet northward across the strike from the shale-limestone block, the strata are overturned. Thus the Holston and Athens on the north limb of this overturned structure may be folded under the older Beekmantown dolomite. It seems possible that the Holston limestone and Athens shale might have been squeezed in the trough of an overturned syncline and forced upward along a shear zone into the older Beekmantown formation. The comparatively incompetent shale and limestone may have "flowed" upward and thus formed a tectonic intrusion into the Beekmantown. The boundaries of the block emplaced in the Beekmantown dolomite are thus local faults that extend downward only into the trough of an underlying overturned syncline (Fig. 1).

The anticlinal structure that contains the tectonic intrusion strikes about N. 35° W. This structure is flanked by a well-established fault on the south and a postulated fault on the north. These faults strike about N. 50° W. and offset the northeast-trending traces of the Pulaski overthrust fault and a postulated overthrust fault tentatively named the Lexington fault. The offsets in the traces of these faults are about a mile long. They may be caused by folding of the major fault planes or by tear faults. They cannot be attributed to the erosion of low-angle faults that dip uniformly toward the southeast. If the offsets are due to folding of the fault planes, these folds must be anticlines that strike about N.

[5] Personal communication.

20° W. The dip of the limbs of these folds should be of about the same order as the dip of the major faults along the northeast-trending traces because the limbs of the folds are highly divergent. However, the fault planes marked by the offsets dip at high angles, whereas the fault planes marked by the northeast-trending traces are low-angle. This marked difference in the magnitude of the dips and the orientation of the postulated folds across the regional strike (about N. 35° E.) casts some doubt upon the occurrence of fault-plane folds. The offsets may consequently be attributed to tear faults. It is difficult to prove the occurrence of such tear faults because the mapping units in the respective fault blocks are very thick and have broad outcrop belts.

If the faults that flank the northwest-trending structure containing the tectonic intrusion are tear faults, the relations may not be coincidental. Possibly the northwest-trending strata owe their orientation to the same differential stresses that caused the tear faults to develop. In other words, the northwest-trending strata may have been drag-folded against the tear in the Lexington fault block. Such drag-folding would cause the thinning of the units in the northwest-trending belt. The Holston formation is notably thinned in the hypothetical drag-folded zone.

PRIMARY LINEATION IN FLUVIAL SANDSTONES A CRITERION OF CURRENT DIRECTION[1]

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ABSTRACT

This paper describes primary current lineation of fluvial sandstones, a type of structure thought to be produced through the streaming of sand grains under the influence of shallow, smoothly flowing water. Field occurrence, validity, and use of the feature are briefly discussed.

Information as to the direction of movement of sediment-transporting currents of air or water is highly desirable in many geologic studies, especially those involving paleogeography. Direct observation, supported by theoretical considerations, has established several criteria which are listed by Frederic H. Lahee[2] as follows: cross-bedding; ripple mark; wave mark; rill mark; and, to some extent, the attitude of included fossils. All of these are megascopic features observable directly in the field. E. C. Dapples and J. F. Rominger[3] have made laboratory and statistical studies which indicate that current direction may be deduced from statistical analysis of measurements of the projections of grains on the bedding plane. They conclude that grains from laboratory fluvial and eolian environments exhibit a pronounced preferred elongation parallel to the direction of flow of the depositing medium and a marked tendency to lie with their larger ends upcurrent. Earl Ingerson[4] has shown in connection with a study of ripple marks that there is a possibility that petrofabric analysis may also be useful in some instances. The two last-mentioned methods require laboratory study with oriented specimens and presumably are most useful where all the usual megascopic evidence is lacking.

The purpose of the present paper is to describe another common feature of fluvial sandstones, here termed "primary current lineation," which may be used in the field as a supplemental criterion of current direction. The term "primary lineation" is used to distinguish this type of structure which originates at the time of deposition of the rock from possible linear structures which may originate through tectonic movements and which are more properly designated as secondary. It consists essentially of a streamlining or streaming effect of sand particles in relatively low and poorly defined windrow-like ridges parallel with the current direction. It is made visible mainly through the light and shadow effects of slight variations in relief upon the bedding planes. Figures 1 and 2 are intended to show the nature of the markings and to illustrate the effect of different angles of illumination in rendering them more noticeable. It should not be inferred that low-angle illumination is essential to the

[1] Published with the permission of the director, Geological Survey, United States Department of the Interior.

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FIG. 1.—Specimen of fluvial sandstone from Salt Wash sandstone member of Morrison formation, Carrizo Mountains, Arizona, showing current lineation. (Specimen photographed under strong oblique illumination coming from above and making an angle of about 10° with the surface. Black strip indicates inferred line of current direction.)

FIG. 2.—Same specimen as Fig. 1, photographed under vertical illumination. Note that lineation is still visible.

use of this feature; lineation is much more evident in gross aspect on larger exposures of sandstone than on small specimens.

Primary lineation in fluvial sandstones is thought to originate in shallow water of moderate velocity and, therefore, is characteristic of laminar flow and absence of turbulence except on a minute scale directly associated with the movement of individual sand grains. Sediments showing this feature are usually divided by flat bedding planes into laminae ranging from $\frac{1}{4}$ to $\frac{3}{4}$ inch in thickness. The same markings and lamination of beds usually persist through several inches or several feet of beds. Cross-bedding and current lineation occur together in sandstone lenses, but lineation is mostly confined to the marginal areas. Cross-bedded laminations are curved and inclined; those showing lineation are flat.

The validity of this criterion has been tested in the field by a variety of observations. Current lineation has been seen on the dry, sandy beds of intermittent streams in the arid regions of western Colorado, but it is apparently rarely formed and is distinctly subordinate to ripple markings in environments of this sort, probably because the flow of such streams is too swift and too turbulent. In all cases it is parallel with the direction of flow of the streams and at right angles to the ripple marks. In the fluvial sandstones of the Salt Wash sandstone member of the Morrison formation, current lineation has been checked many times and found to be in perfect agreement with the evidence of current bedding. It has been noted in fluvial sandstones of several different terrestrial formations of Paleozoic and Mesozoic age at many places in the Colorado Plateau and is assumed to be geologically widespread.

Current lineation, at least megascopically, limits the depositing current to two possible opposing directions and in this respect is analogous to flow structures in igneous rocks. Which direction is the correct one must be ascertained by reference to other evidence, usually current bedding. This is not a serious deterrent to the use of current lineation, since any conclusions regarding source, direction of flow, and general nature of streams responsible for fluvial deposits should be made on the basis of statistical analysis involving numerous observations. Isolated and scattered readings are likely to be entirely misleading and erroneous. For this reason all possible field evidence should be recognized and used. It has been the experience of the writer in making a detailed study of the sedimentary features of the Salt Wash sandstone member of the Morrison formation that the use of current lineation increases the potential number of observations which may be made in any one area by at least 30 per cent. In many small outcrops it is the only visible clue; a few inches of exposed rock are usually all that are needed for a good lineation reading, while several square feet or even yards must be visible for current-bedding determinations. Although current bedding is undoubtedly more useful and easier to interpret, current lineation is a valuable adjunct in studies of this kind.

REVIEWS

Our Oil Resources. Edited by LEONARD M. FANNING. New York and London: McGraw-Hill Book Co., Inc., 1945. Pp. 331. $4.00.

Articles and contributors: "The Role of Private Enterprise in the Development of Oil Resources," John A. Brown, late president, Socony-Vacuum Oil Company, Inc.; "American Oil Companies in Foreign Petroleum Operations," Eugene Holman, president, Standard Oil Company (New Jersey); "Conservation of Our Oil and Gas Resources," J. C. Hunter, president, Mid-Continent Oil and Gas Association; "Exploration Technology," O. D. Donnell, president, Ohio Oil Company, and A. Jacobsen, president, Amerada Petroleum Company; "Production Technology," John M. Lovejoy, president, Seaboard Oil Company; "Refining Technology," Robert E. Wilson, chairman of the Board, Standard Oil Company (Indiana); "The Earth's Petroleum Resources," Wallace E. Pratt, vice-president, Standard Oil Company (New Jersey); "Estimate of United States Oil Reserves," American Petroleum Institute; "Our Natural Gas Resources," Lyon F. Terry, second vice-president, Chase National Bank, New York; "Cost of Storage of Military Reserves of Crude Petroleum or Products," F. W. Abrams, vice-president, Standard Oil Company (New Jersey); "Our Reserves of Coal and Shale," K. C. Heald, chief geologist, Gulf Oil Corporation, and Eugene Ayres, chief chemist, Gulf Research and Development Company; "Oil from Coal and Shale," Robert E. Wilson, chairman of the Board, Standard Oil Company (Indiana); "The Public Domain and Naval Reserves," W. H. Ferguson, vice-president, Continental Oil Company; "Lands of the United States," A. C. Mattei, president, Honolulu Oil Corporation; "Status of Federal Lands," L. T. Barrow, vice-president, Humble Oil and Refining Company; "Capital Employed in the Petroleum Industry," Joseph E. Pogue, vice-president, and Frederick C. Coqueron, petroleum analyst, Chase National Bank, New York; and "The American Oil Industry," Leonard M. Fanning.

The problem of the amount of our oil resources is not simple. That it cannot be stated in terms of barrels or of years' supply is well brought out by this symposium written by as authoritative a group of authors as it would be possible to assemble. Several of the articles have been previously published, and there is some repetition of ideas and material, as might be expected in a series of articles such as this. The over-all result, however, is a fair picture of the complex nature of our oil and gas resources by a group of executives actively and successfully engaged in the discovery, production, and refining of oil and gas. The volume is well worth reading by anyone interested in the oil industry and the nature of its resources.

The general theme of the volume is optimistic as to the resources of oil and gas available for our future needs, *provided* that the oil industry is permitted to continue operating under an economy of free enterprise. These resources within the United States consist of the known reserves on the order of twenty billion barrels of crude petroleum and 110 trillion cubic feet of natural gas; the undiscovered oil and gas reserves; improved production methods, refinery techniques, and more efficient use of the products; the coal which can be transformed into gasoline and other products, chiefly by the Fischer-Tropsch process; and the oil shale which will yield large quantities of oil products through destructive distillation. The chief resources outside the United States, which may become available through import, are the large discovered and undiscovered petroleum reserves in many parts of the world, chiefly the Near East, the East Indies, and northern South America, a substantial percentage of which are now owned by American companies. Above all, however, "our greatest, though intangible, oil resource lies in the ability, energy, and brains of operating, engineering, and research talent working coordinately in the American private oil industry."

Numerous tables and charts show the essential data in convenient form. Of particular interest, perhaps, are those charts showing the steady expansion of the industry in the United States through good times and bad and whether we were at war or peace. Fundamentally, the expansion was based on the ability of the industry to discover enough oil to meet the demand,

and this ability to discover is dependent on many interrelated techniques and skills. Basically, discovery is geological in approach, but the methods by which the information is obtained—such as improved logging of wells, the use of geophysical methods for structural mapping, the advent of better steels, thereby making deeper drilling possible—all contributed to the result. These techniques and skills were developed largely because of the favorable political and economic climate in which the industry has operated, and one of the essentials of the continued expansion of the industry is in maintaining enough stimulation of effort to justify the drilling of the thousands of exploratory wells needed every year.

Not only have our oil resources increased through discovery of new reserves over the years but they have been multiplied even more by improved technologies and engineering skills in their production, manufacture, and use. Thus, improved production methods since 1918 are estimated to have added 35 per cent, or seventeen billion barrels, to the oil recovery formerly expected from the amount of oil discovered to date. Of the present estimated known reserves of twenty billion barrels, approximately eleven billion barrels, or 55 per cent, are estimated to be available through improved technology in drilling and producing alone. In a like manner, improved techniques in refining have increased the gasoline yields from around 25 per cent in 1918 to around 45 per cent in 1941, and it is anticipated that when the modern catalytic cracking-units have been generally installed, the gasoline yields from crudes will be near 57 per cent and limited only by the public demands for other products. The fear is expressed that the danger of the future will not be a shortage of raw materials but rather the devitalization of the entire research program through increased governmental domination, regimentation, and interference with the free play of technology and competitive enterprise.

The American oilman has found oil and gas in adequate amounts within the United States, and he has also played a leading and vital part in the exploration and development of oil and gas resources in many foreign lands. As a result of his aggressive policy, in 1939–41 American companies owned (excepting in the U.S.S.R.) approximately 23 per cent of the foreign refineries, 23 per cent of foreign oil production, and over 24 per cent of foreign oil reserves. These foreign reserves have been increased, until in 1944 it was estimated that the amount of American ownership is nearly 40 per cent, or a total of over ten billion barrels. This is nearly one-half the reserves known in the United States.

The record of gas resources runs parallel to that of oil. They are estimated by the Petroleum Administrator for War to be on the order of 110 trillion cubic feet of known producible reserves, or twenty-seven to thirty-three times the rate of annual withdrawal. This is considerably less than the later figure of 140 trillion cubic feet given by De Golyer before a committee of the Senate, June 19, 1945. As with oil, it is believed that the greatest future gas resource lies in the undiscovered reserves. The basis for this belief is in the geological interpretation of the unexplored regions of the country, which for both oil and gas are expected ultimately to develop at least as much more as has been found in the past.

One continuing problem of the oil industry has been conservation. Much progress has been made in this direction through the creation of the Interstate Compact in 1935. It now has a membership of thirteen states and includes more than 80 per cent of the annual oil production. The essence of modern conservation practice is the realization that an oil and gas reservoir is a physical unit; and, when its energy is controlled and utilized as a whole, the result is the recovery of a greater amount of oil from a given pool. Oil, having no inherent energy to lift it to the surface, is dependent on either (1) the expansion of gas dissolved in it, (2) displacement of oil by the influx of water from below, or (3) displacement of the oil by downward expansion of the free gas cap on the pool. In wells which have reached the pumping stage, gravity brings oil from the reservoir rock into the borehole. Thus conservation—"the prevention of the waste of an urgently needed natural resource"—is becoming more and more solidly based on sound engineering concepts of the conditions which prevail in the oil and gas reservoir.

While satisfactory progress is made in the field of conservation, the symposium expresses alarm over the effect of the increasing amounts of land being acquired by the federal government and thereby being withdrawn from oil and gas exploration. In amount it ranges to over 45 per cent of the lands in some of the western states and from 1 to 8 per cent for most of the oil-producing states east of the Rockies.

Several of the articles are of particular interest to geologists. That by John M. Lovejoy is a concise statement of the fundamental principles involved in the production of oil and gas and the relation of these phenomena to the geological conditions surrounding the reservoir. These principles, chiefly developed by petroleum engineers, have permeated the thinking of the entire industry on production and conservation problems.

Wallace Pratt, speaking from the vantage point of an executive of the largest oil company in the world, again reiterates his philosophy of the abundance of undiscovered oil and gas throughout the world and concludes that "there will be no sudden failure of our supply of petroleum. . . . . We shall have timely warning. The new industry of making liquid fuels from other raw materials will establish itself as rapidly as the petroleum supply fails . . . . it is hardly conceivable (unless wars are to continue unceasingly) that the United States will suffer a critical shortage of liquid fuels within the foreseeable future."

The overshadowing importance of coal as a possible substitute oil resource is brought out in the article by K. C. Heald and Eugene Ayres. The coal resources of North America are such that when gasoline and other products obtained from them compete in price with petroleum products, domestic requirements will be met for generations. The most likely method of obtaining gasoline and other products from coal is in the Fischer-Tropsch process, which has been extensively used in Europe but which so far has not been commercially utilized in the United States. This process uses two steps: (1) the gasification of any kind of coal or lignite and (2) the catalytic conversion of the synthesized gas to petroleum products. It may also be used directly on natural gas, eliminating step 1.

Since any kind of coal may be used in the Fischer-Tropsch process, there are on the order of four trillion tons of known coal source material in North America from which it is estimated some six trillion barrels of gasoline might be manufactured. This compares with an estimated fifty billion barrels of gasoline from oil shale, two billion barrels of gasoline from tar sands, two to four billion barrels of gasoline from natural gas, and ten billion barrels of gasoline from known crude-petroleum reserves. Costs are the limiting factor at present and range from 9 to 18 cents per gallon for Fischer-Tropsch gasoline from coal, 10 to 15 cents per gallon for gasoline from oil shale, 8 to 12 cents per gallon for gasoline from tar sands, 5 to 9 cents per gallon for gasoline from natural gas, against a present cost of 5 cents per gallon for gasoline from crude petroleum. The investment required per barrel of gasoline per day's capacity is also higher, being from $2,800 to $10,000 for the Fischer-Tropsch process compared to $1,400 to $2,800 for the modern refinery using crude petroleum.

Measured by its accomplishments in both peace and war, the American oil industry has much to be proud of. It is a great industry. Because it touches everyone in some manner or other, the adequacy of its resources—crude oil and natural gas—in terms of national needs is rightfully a subject of public concern. This volume, written by top-notch executives of this industry, many of whom are geologically trained, should do much to dispel some of the popular misconceptions concerning the nature of our oil resources.

A. I. LEVORSEN

Introduction à la lecture des cartes géologiques. By ANTOINE BONTE, Assistant de Géologie à la Faculté des Sciences de Besançon. Paris: Masson et Cie, 1945. Pp. 239; figs. 103; pls. 8.

Introduction à la lecture des cartes géologiques is a book specifically on the subject of the geologic map. As M. Eugene Raguin states in the Preface, "The map is together the goal and the instrument of geologic studies." With this in view Antoine Bonte proceeds to show the problems connected with mapping and how it should be done. At the same time he indicates the use of the factual record as it appears on the map as an instrument in further work. Certain aspects of general geology, topographic maps, structure, and stratigraphy as they pertain to a geologic map are also discussed and well illustrated.

Texts on general geology, stratigraphy, structure, and descriptive geometry cover, in part, the material in this book. Usually, however, such books do not present the geological-map aspect of these subjects. In this book Bonte has concentrated on the geological map and has done an outstanding piece of work, which is both stimulating and informative.

A summary of the Table of Contents is as follows:

Chapter i, "The Fundamental Principles of Geology": Stratigraphy, with emphasis on the principles of superposition and continuity.

Chapter ii, "Notes on Tectonics": Types of faults, folds, and nappes.

Chapter iii, "Topographic Maps": Contour and hachure.

Chapter iv, "Geological Maps": French.

Chapter v, "Principal Types of Structure": Some theoretical considerations in connection with them.

Chapter vi, "Instructions on the Geologic Maps": Profiles and geological cross sections and some geomorphology.

Chapter vii, "Geological Mapping": What is needed, and how geological mapping should be done.

Chapter viii, "Graphic Constructions Relative to Geologic Maps": Various applications of descriptive geometry to the problems of geological mapping; exercises.

Annexes A to G: Charts and tables of various types, such as conversion tables, the French stratigraphic column, and keys to French geological maps.

The first two chapters deal interestingly with some of the basic fundamentals of geology, but this material is treated only as it applies to the geological map. The nomenclature of geologic structures is given and illustrated along with a very useful description of nappe structure.

Chapter iii is very informative, discussing, in addition to the contour map, the hachure map, which is an unfamiliar type in the United States. The explanation of hachure-map construction is both interesting and useful.

Chapter iv is valuable for anyone wishing to use French geological maps, as it describes the various types of geological maps available. Anyone having a special interest in a particular section of France may obtain maps of this area by consulting Annexes F and G at the back of the book.

In chapter v, on structure, the author considers the outcrop of beds. The chapter is introduced by examining the appearance of the outcrop of beds having a variety of dips on a fixed slope. This section is well illustrated with block diagrams. The relation between width of outcrop and thickness of bed is also discussed, with numerous formulas to fit all cases. The last part of the chapter is devoted to the characteristic pattern of geologic structures on a map and some of the interpretation and errors of interpretation.

Chapter vi could really be divided into two chapters; the first part deals with general material on the geological map, such as profiles and the construction of geologic cross sections; the last part describes the French stratigraphic column and how some of these formations appear in the field.

The last two chapters would probably be of greatest interest to American geologists. In chapter vii the subject of geological mapping is presented in a different light. All the necessary precautions and "do's" and "don't's" as well as the general procedures are discussed in a refreshing manner. Some of the techniques described are more European than American, but the fundamentals are the same.

The final chapter, viii, on graphic construction, is an excellent discussion. Basic methods of gaining more information from already known facts are diagramed and very well presented. A method of drawing contours on a horizon is described, as well as of getting attitudes of a bed from various points on the same horizon; determining true dip from apparent dip; and various other problems of that nature. Diagrams are a feature of the book, and in the section dealing with geometric constructions there are many useful examples. The last ten pages of the chapter are exercises in the application of the principles presented in the book. There are only four exercises, but each one amounts to more than one simple problem. Two of the problems are completing of a map from known data and making a geologic map from two cross sections. These are excellent problems for anyone.

Bonte felt that there was no work in French which covered this subject and that such a book was needed. It is probably equally true that there is no work in English which covers the subject in the same manner as he has. This book was written from lecture notes; and, in so doing, the author preserved an understanding for the problems of a student. This has produced an excellent and very readable book.

GEORGE J. BELLEMIN

The Submarine Relief off the Norwegian Coast with Bathymetrical Map in Seven Sheets of the Norwegian Coastal Waters and Adjoining Areas. By OLAF HOLTEDAHL. Oslo: Det Norske Videnskaps-Akademi, 1940. Pp. 43; figs. 7; pls. in pocket 6.

The report is essentially a summary description and interpretation of seven colored bathymetrical maps which portray submarine features along the entire Norwegian coast. It includes the following chapters: "Introduction,"

"Description of Some Relief Features as Seen in the Maps," "Notes on the Dredgings Carried Out on Board M/S 'Gunnerus' 1931 and 1932 outside the Romsdalsfjord District," "General Remarks," and "References." The maps, based on the official Norwegian charts, use Mercator's projection and vary in scale from about 1:400,000 to about 1:600,000. The contour-line interval is 10 m. and the color interval 100 m. All data from previously printed official charts and other maps, as well as unpublished recent soundings, have been compiled for these charts. The plates include a composite map of the submarine relief showing the major physiographic features, maps of local areas, and numerous submarine profiles.

The submarine coastal area is dominated by the broad Norwegian shelf (50–200 km. wide), which is regarded as part of the extensive shelf areas of the North Sea to the southwest and Barents Sea to the northeast. Two major tectonic lines outline the shelf: (1) "a zone of dislocation of first order" at the outer margin of the shelf which separates the Eurasiatic land block from the ocean basin and (2) "a zone of fracture of more local character," which separates the Scandinavian land mass from the shelf region. The latter zone is described in detail and is revealed on the maps by linear submarine scarps and troughs margining either the strand flat or the present coast. The scarps in particular have regular, unbroken arcuate trends and are distinct from the pattern of intersecting fractures in the adjoining land mass. They are considered marginal fracture lines of Cenozoic age along which the entire Scandinavian block was uplifted and tilted eastward. This concept of recent uplift, previously advanced by the author along with Nansen, Sederholm, G. De Geer, and others, is substituted for the older view that the Scandinavian mountain range is simply a relict of the higher ancient Caledonian range. In a previous publication (1929) the author suggested that the marginal scarps might mark the contact between crystalline and less resistant younger (Mesozoic?) rocks. The dredgings, however, give no positive evidence, as they indicate glacial bottom materials composed largely of crystalline rocks of Norwegian types.

Except for the Norwegian Channel off the south coast, which is considered a modified tectonic depression, the secondary relief features of the shelf are largely glacial in origin and include: submerged fiord mouths and thresholds, ice-scoured depressions, and moraines. The existence of lobate shelf glaciers is indicated by the moraines, and comparison is made with the Pleistocene glacier tongues along the eastern side of the Andes. The fiords are believed to be mainly the product of ice erosion rather than of faulting. In addition to the submerged glacial features, shallow transverse channels, which in many places can be related to major valleys on the mainland, are interpreted as fluvial and glaciofluvial drainage lines.

Repeated oscillations of sea-level are implied by the shelf features, and three possible submarine levels indicating lower relative sea-levels are noted: (1) 260–70 m., evidenced by abrasion platforms, fiord thresholds, and the flat central part of the Norwegian Channel; (2) 300–400 m., indicated by outer shelf moraines; and (3) below 400 m., suggested by the possible fluvial or glaciofluvial alluvial plain along the northern part of the Norwegian Channel.

It is regrettable that the author's original plan of including a treatment of the geomorphology of the adjoining mainland had to be postponed. This is important for an understanding of the submarine relief, and it is hoped that its appearance will not be long delayed.

LELAND HORBERG

On Major Tectonic Forms of China. By T. K. HUANG. ("Geological Memoirs," Ser. A, No. 20.) Pehpei, Chungking: National Geological Survey of China, 1945. Pp. 165; pls. 8.

Asia, the greatest of continents, probably can add more to our understanding of the earth's deformative history than any other continent. Central and eastern Asia are particularly rich in tectonic features of global importance, as yet rather spottily known. Very welcome, therefore, is this effort to fit together the major tectonic forms of China in a unified treatment which reaches as far as the Karakorams and Lake Baikal.

In his introduction, which is essentially a genetic classification following Stille and Argand, the author discusses continents and geosynclines, orogenic and epeirogenic movements, foundation folds, and, finally, orogenic structures grouped in four principal categories—*Deckengebirge*, *Faltengebirge*, *Bruchfaltengebirge*, and *Blockgebirge*. He presents China's orogenic cycles since the Cambrian as the Caledonian; the Variscan, comprising three subcycles from late Devonian to the end of the Permian; Indosinian (late Trias to Lias); Yenshanian in

three phases (late Jurassic to end of Cretaceous); and the Himalayan in three phases corresponding to those of the Alps.

In the light of these classifications by structures and by time, successive chapters describe the pre-Cambrian massifs, the Caledonides, Variscides, Indosinides, etc. Each comprises many individual geographic units, which are seemingly about as adequately treated in concise form as is possible at present. Following this analysis of the major tectonic features of China and their relationships, chapter ix explains their history and successive development through the geologic ages.

Progressing to larger relationships, chapter x, "The Geotectonic Make-up of China," develops various principles of continental evolution substantiated by China's contributions. The discussion includes: (1) areas of crustal weakness versus areas of crustal strength; (2) the order and intensity of folding in a given orogenic cycle; (3) consolidation, migration of geosynclines, and growth of the continent; (4) arcuate fold systems and their origin; and (5) *Leitlinien* and major tectonic types The southward migration of geosynclines, with their subsequent fold ings outward from the old Angaraland massif is our most declared example of the growth of a continent. Subsequent chapters treat the igneous activity and metallogenesis by epochs and by provinces.

To anyone interested either in the regional tectonics of China or in the part which southeastern Asia has played in the general tectonic development of the globe, this report can be strongly recommended.

R. T. C.

India, Part I: *Physical Basis of Geography of India*. By H. L. CHHIBBER. Benares: Nand Kishore & Bros.; 1945. Pp. 282; figs. 19; pls. 10. Rs. 5; sh. 9.

Recognizing that the physical basis of the geography of a country is necessary for a proper grasp of its geography as a whole, the author has prepared this short treatise to meet a generally felt need. The chapters of the first half of the book present in succession the physical divisions, mountains, plateaus, rivers, lakes, glaciers, earthquakes, coastline, volcanoes, and the hot springs and mineral waters of India. They are largely descriptive and informative, presenting briefly the most important facts. Some readers, however, will be surprised by the statement on page 14: "This mountain [K2 28,250 ft., generally considered the world's second highest peak] was ascended by the Duke of Abruzzi in June, 1909, and it represents the highest altitude ever climbed by a human being."

The geologic rock systems of India are described in concise fashion for the reader who wishes a general survey. The "Making of India" explains the dynamic history, which is amplified by a later chapter on the "Structure of India." Soils, soil erosion, and fertilizers are given relatively full treatment, being particularly vital to a populous country like India.

R. T. C.

German-English Science Dictionary. By LOUIS DE VRIES. 2d ed. New York and London: McGraw-Hill Book Co., 1946. Pp. xiv+558. $4.50.

The first edition of this dictionary, prepared with the collaboration of members of the graduate faculty of Iowa State College, was reviewed in the *Journal of Geology*, Vol. XLVIII (1940), p. 1022. The new revised edition has been enlarged, particularly in the fields of chemistry, biology, agriculture, and forestry.

R. T. C.